

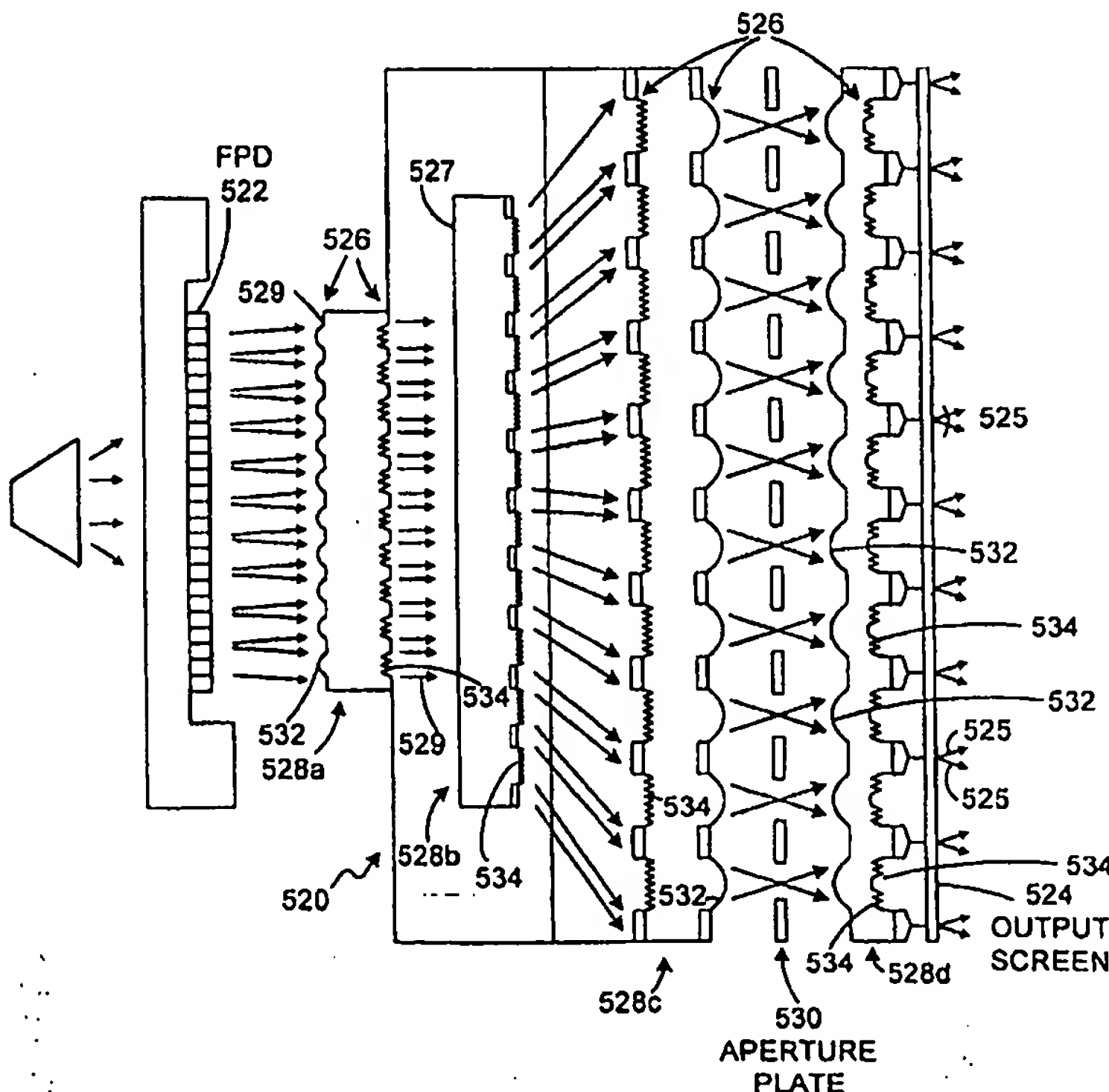
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(54) Title: LENSLET ARRAY SYSTEMS AND METHODS		
(57) Abstract		

A stacked array (figure 2) magnifier (SAM) forms a magnified, demagnified or unit image of an object. The SAM includes one or more non-refractive lenslet arrays and one or more refractive lenslet arrays to form a plurality of lenslet channels (54a-54b). Each lenslet channel has at least one refractive lenslet and at least one non-refractive lenslet. SAMs are combined and tiled (figure 4) to form a scaleable display of flat panel displays. Multiple SAMs are used to increase magnification selectively. Hybrid lenslet arrays of the invention are also useable for optical processing and non-imaging applications.



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Lenslet Array Systems and Methods

1 Background

2 Imagery is presented in many forms. In the classical optical camera, for example, light
3 energy from an object scene is focused through glass optics onto a film formatted image plane
4 where light sensitive film records the scene. Typically, the film format corresponds to "35mm"
5 film, which translates to maximum linear dimensions of 36.3mm (horizontal) by 24.2mm
6 (vertical), or a vertical-to-horizontal ratio of 3:2.

7 In the electronic age, the classical film-formatted camera is being quickly replaced by
8 the solid-state camera utilizing charge coupled devices such as the "CCD" array. Typically, the
9 CCD array is formatted to conveniently correlate with the computer display screen, which has a
10 horizontal-to-vertical aspect ratio of 4:3. In this manner, the CCD array and computer display
11 are matched on a pixel-to-pixel basis.

12 However, regardless of the high quality image presented by the classical film-formatted
13 camera, its optics and housing are unsuitable for application with the CCD array. Accordingly,
14 as users convert to digital cameras, their older film-formatted cameras shall become obsolete.
15 Not only will the typical user have to buy a new camera, i.e., the digital camera, she will discard
16 or retire the film-formatted camera, creating both cost and waste.

17 It is, accordingly, one object of the invention to provide apparatus and methods for
18 adapting film-formatted cameras to solid state devices such as the CCD array in a compact and
19 useful manner. A corollary object of the invention is to provide reimaging methods to achieve
20 selected magnification and/or demagnification for each of the tangential and sagittal axes.

21 The prior art is known to have created optical systems for relaying and magnifying or
22 demagnifying optical images by way of an optical system such as a relay lens. Specifically, in
23 the prior art, it is known that a relay lens can be used to relay one image plane to another image
24 plane at a selected magnification (or demagnification) ratio. However, such an arrangement is
25 unwieldy and would generally double the size of the classical camera, making the approach non-
26 practical as a solution to the above-described problem. Further, it is very difficult, and thus
27 costly, to simultaneously provide selected magnifications for both of the tangential and sagittal
28 axes. By way of example, it is known that an astigmatic optical element provides such a
29 bifurcated magnification; however, this element requires additional aspheric processing, adding
30 cost, time and complexity to the manufacturing process.

31 The problems discussed above are symptomatic of a wide range of display problems and

1 inconveniences experienced today. In the electronic and medical world, for example, imagery is
2 often displayed on a television (TV), a computer display, the liquid crystal display (LCD), the
3 cathode ray tube (CRT), light-emitting diode arrays, and back projection systems. It is often
4 desirable, however, to illustrate the electronic display in a different format such as to a wider
5 audience on a large format display. In the prior art, for example, complex projection systems are
6 sometimes used to relay a smaller electronic display onto a large, reflective surface such as a
7 white wall or a projection screen. However, it is widely understood that projection display
8 systems are large in size, expensive, and heavy; and they inefficiently consume large amounts of
9 electrical power. They are also generally limited to use in darkened areas due to low luminance
10 output and poor efficiency.

11 An electronic display that is generally defined as a Flat Panel Display (FPD) has other
12 difficulties that are not adequately addressed in the prior art, such as limitations in luminance
13 and angular view. The active matrix thin film transistor liquid crystal display (AM-TFT LCD),
14 the passive LCD, the field emission display (FED), and other FPDs (such as plasma displays and
15 electroluminescent displays) each have characteristic angular fields due to inherent construction,
16 polarizing filters and fore- and back-light characteristics (if required). One example of the
17 angular limitations inherent in a FPD is readily seen in observing a portable computer screen
18 from different angles: the portable FPD is barely visible, if at all, from viewing angles greater
19 than about forty-five degrees from the normal to the screen surface.

20 The angular and luminance limitations associated with viewing a FPD are thus
21 significant. Most observers prefer to view an image that is highly uniform in luminance over a
22 wide field angle. This further compounds the difficulty in converting the FPD to a large format
23 display. In addition, daylight viewing and the suppression of glare often necessitate additional
24 screens or intermediate optics between the FPD and the observer, adding other costs and
25 complexity. In certain applications, the prior art has attempted, without great success or
26 efficiency, to improve the field of view of the FPD through the addition of diffractive spatial
27 filters placed adjacent to the FPD screen.

28 There is the need, therefore, of enhancing the performance of the FPD. It is, accordingly,
29 an object of the invention to provide apparatus and methods for enhancing the luminance and
30 field of view of the FPD. A further object of the invention is to provide systems for converting
31 the FPD to a large format display with improved luminance and field of view.

1 Highly commercial electronic displays have still other difficulties. For example, very
2 large commercial advertising and stadium-sized matrix displays are assembled using tiles of
3 bulbs, CRTs, light emitting diodes (LEDs), or LCD panels. Not only are these systems limited
4 in resolution, color (note, e.g., that LEDs are typically one color) and general optical
5 performance, they are expensive, costing in the neighborhood of \$100,000 per square meter.
6 They additionally have low reliability standards and few specifications or limitations on weight,
7 power consumption and efficiency.

8 It is, accordingly, an object of the invention to provide a system which transforms the
9 image presented by an electronic display - such as the LCD, the CRT, the FPD, phosphor
10 displays, an array of LEDs, a computer screen, and a pixelated object - into a reformatted image
11 with enhanced or modified features, such as with selected magnification, astigmatism, distortion,
12 optical correction, optical processing, and Fourier content.

13 Another object of the invention is to provide apparatus and methods for magnifying or
14 demagnifying an image of an object with a compact and substantially monolithic optical system.

15 Still another object of the invention is to provide methods of manufacturing and
16 constructing combinations of lenslet arrays to achieve magnification or demagnification
17 selectively.

18 Yet another object of the invention is to provide optical correlating apparatus and
19 methods for conveniently achieving Fourier processing of an electromagnetic field.

20 These and other objects will become apparent in the description which follows.

21

22 Summary of the Invention

23 As used herein, "magnification" is sometimes used to denote both magnification and
24 demagnification. Accordingly, "magnification" is sometimes used herein to denote a
25 magnification of greater than one, a demagnification of less than one, and unit magnification.

26 As used herein, a "lenslet array" refers to an array of microlenslets that are arranged into
27 an optical substrate surface. A single lenslet array can therefore include an array of refractive
28 lenslets or an array of non-refractive lenslets. As used herein, "non-refractive lenslets" generally
29 mean diffractive lenslets. However, non-refractive lenslets can include holographic steering
30 lenslets, phase modulating lenslets, and index modulating lenslets (including gradient index
31 modulation formed through ion implantation and ion exchange, and effective index modulation

1 using nanometer cuts within a substrate surface). A lenslet array is formed with an optical
2 surface substrate which is typically planar except for the micro-features of the microlenslets.
3 However, those skilled in the art will appreciate that lenslets arrays can be formed internally to
4 an optical substrate - and thus not on the surface - or onto curved surfaces (e.g., macrolenses)
5 which provide additional optical power.

6 A "stack" as used herein refers to a plurality of lenslet arrays arranged substantially
7 adjacent to one another to operate as a single optical system. Generally, a stack has at least two
8 lenslet arrays forming an array of "lenslet channels," each of which has at least one refractive
9 lenslet and at least one non-refractive lenslet. In order to achieve radiation transfer along each
10 lenslet channel, each lenslet array in a stack typically has like numbers of lenslets so that there is
11 a one-to-one correspondence between the lenslets of one channel (that is, each lenslet of each
12 array has a corresponding lenslet in each of the other arrays; the corresponding lenslets forming
13 the channel between the several arrays).

14 As used herein, a "tile" refers to mosaic of like elements to operate, substantially, as a
15 single element. In the typical case, a tile can be formed, for example, by an array of like lenslet
16 array stacks which are abutted, end to end, so as to substantially function as a single stack.

17 As used herein, a "stacked array imaging system", or "SAM," refers to an imaging
18 system such as a stack arranged to view and image objects. For example, a SAM can include a
19 magnifying or demagnifying optical system.

20 As used herein, "pixelated" refers to the quantized nature of certain objects and images.
21 For example, most computer displays are made up of a thousands of pixels emitting light energy
22 at the command of the computer's central processing unit (CPU). Such a display is "pixelated"
23 since it is quantized. By way of another example, a solid state device such as a CAMCORDER
24 records continuous, real-world imagery via a CCD array; and the data captured by the
25 CAMCORDER is thus pixelated or "discrete." High speed computing via fiber-optics and
26 electrical paths can also be "pixelated" in that data, often made up of large digital words, are
27 processed in a massively parallel fashion (sometimes denoted herein as "massive parallel
28 processing" or "MPP"). By way of comparison, real world objects like a human being are
29 continuous; and a picture (i.e., an image) taken of real world objects onto film emulsion is also
30 continuous since it is not quantized.

31 As used herein, a "Micro Electromechanical System", or "MEMS", refers to an actuator

1 or electromechanical device or micro miniature machine that is placed between stacks or is
2 constructed onto a stack element. For example, a SAM consisting of a stack of fixed lenslet
3 arrays can have a fixed magnification at a fixed set of imaging conjugates. By building a SAM
4 with an active actuator mechanism or MEMS at an intermediate image plane, then the
5 magnification of the imaging system is adjustable and variable according to an electronic
6 impulse signal to the actuator, thereby changing the spacing between the image forming stacks.
7 By way of comparison, an autofocus camera has a motorized screw mechanism for movement of
8 the optical elements in the camera objective in order to change the focus and/or f-stop of the
9 camera.

10 In one aspect, the invention provides a stacked array magnifier (SAM) for forming a
11 magnified image of an object. The SAM includes one or more non-refractive lenslet arrays and
12 one or more refractive lenslet arrays to form a plurality of lenslet channels. Each lenslet channel
13 has at least one refractive lenslet and at least one non-refractive lenslet, and the lenslet channels
14 between at least two adjacent arrays are sloped relative to an optical axis between the object and
15 the image. The sloped lenslet channels that are further from the optical axis have larger slopes
16 than the sloped lenslet channels closer to the optical axis. Together, the slopes of the several
17 channels provide selective magnification between the object and the image.

18 In another aspect, the lenslet arrays form a stack between a first surface facing the object
19 and a second surface facing the image. The lenslet channels extend further from the optical axis
20 at the first surface, and closer to the optical axis at the second surface, thereby providing
21 demagnification of the object at the image. Such an aspect can include a solid state focal plane at
22 the image plane which is substantially perpendicular to the optical axis so as to receive
23 electromagnetic radiation from the object.

24 In still another aspect, the lenslet arrays form a stack between a first surface facing the
25 object and a second surface facing the image. The lenslet channels extend further from the
26 optical axis at the second surface and closer to the optical axis at the first surface, thereby
27 providing magnification of the object at the image.

28 In accord with the invention, the lenslet channels typically have clear aperture diameters
29 of between about $5\mu\text{m}$ and $1000\mu\text{m}$. As shown herein, certain experimentation was conducted
30 with clear apertures of about $168\mu\text{m}$.

31 In another aspect, the stack can include a macrolens - i.e., a lens element that is

1 substantially larger than any of the lenslets - that is arranged between at least two adjacent
2 arrays. The macrolens is included, generally, to add optical power between the object and image.

3 To effect continuous imaging, in another aspect, a plurality of lenslet channels are
4 arranged so as to contribute to each point in the image. In order to provide an erect image, the
5 SAM of this aspect must have $2n+1$ internal images, where n is an integer.

6 Lenslet arrays can be constructed and arranged according to the invention to provide a
7 magnification ratio of less than about 8:1 between the object and the image. A second stacked
8 array magnifier can thus be used, in sequence, to provide secondary magnification of the object
9 to a secondary image along the optical axis. The second SAM is substantially similar to the first
10 SAM, though the magnification need not be the same. In this manner, a magnification from each
11 SAM is multiplied - e.g., 8:1 x 8:1, which provides an overall magnification of 64:1.

12 In other aspects, the SAM is transmissive to visible electromagnetic radiation between
13 about 400nm and 750nm. As such, a CCD array can be conveniently arranged at the image and
14 substantially perpendicular to the optical axis so as to collect the visible electromagnetic
15 radiation from the object. However, SAMs of the invention can be made to function with any
16 range of wavelengths, such as the ultraviolet and infrared.

17 For example, the SAM can also be made transmissive to infrared electromagnetic
18 radiation; and can include "uncooled" microbolometer arrays or other IR detectors, e.g.,
19 HgCdTe, at the focal plane. In another aspect, the lenslet arrays are made transmissive to visible
20 electromagnetic radiation between about 540nm and 580nm, which corresponds to certain
21 phosphor display devices in the medical arts. Accordingly, the SAM material is optimized in
22 transmission and diffraction features within the wavelength of interest. Note that the non-
23 refractive lenslets have greater efficiency for a smaller waveband when optimized to that
24 waveband. By way of example, those skilled in the art should appreciate that non-refractive
25 lenslet arrays which include blaze grating features have the best efficiency at the designed
26 wavelength. Blaze gratings can be optimized in angle to provide peak diffraction efficiency, for
27 example, at phosphor emission wavelengths.

28 To restrict the FOV and to reduce cross-talk, at least one refractive lenslet array of the
29 invention can operate to form an intermediate image of the object and within the SAM. A field
30 stop is then located at the intermediate image - or very near to the image - to limit the field of
31 view of one or more lenslet channels. Similarly, a Lyot stop can be located at the intermediate

1 image to reduce cross-talk from out-of-field radiation (preferably, the stop reduces stray light
2 cross-talk to less than about 10% of all of the electromagnetic radiation transmitted from the
3 object and to the image). To be most effective, the stops should be within about a blur distance
4 from the internal SAM image, whereby the defocus wavefront error is less than about $\frac{1}{4} \lambda$.

5 In a preferred aspect of the invention, each lenslet channel includes an array of three
6 lenslets at each lenslet array. These three lenslets are transmissive to a unique RGB color such
7 that substantially any color can be transmitted along each channel. At the same time, each of the
8 non-refractive lenslets are preferably optimized for optical efficiency corresponding to the RGB
9 color associated with its channel.

10 The invention also provides for interlaced imaging, or for pixelated imaging so as to
11 produce an array of discrete images of the object. In this latter aspect, the FOV of each channel
12 is substantially non-overlapping with adjacent channels to accommodate efficient discrete
13 collection by a solid state sensor.

14 The lenslet arrays of the invention can also include, in another aspect, one or more
15 optical coatings to improve optical transmission through one or more lenslet channels.

16 In one aspect, a SAM is constructed and arranged so as to have an overall f-number that
17 is less than any of the lenslet f-numbers. For example, if each of the lenslet channels is
18 constructed and arranged so as have an f-number of $f/1$ or greater, the overall f-number of the
19 magnifier is less than about $f/1$.

20 In yet another aspect, the SAM of the invention can include means for creating
21 diffraction orders of electromagnetic radiation transmitted between the object and the image, the
22 orders being sufficient to provide greater than approximately 90% efficiency. Similar means can
23 also be included to improve the imaging resolution within the image with a modulation transfer
24 function of greater than about 10% at image frequencies greater than about 500 lp/mm.

25 In certain aspects, lenslets of the invention can include refractive surfaces with aspheric
26 shapes. In other aspects, means for reducing distortion is included such that the image distortion
27 is less than about 2%. By way of example, the distortion reduction means can include edge
28 lenslets having more or less power than other lenslets within the same array. These edge lenslets
29 are adjacent to one or more edges of the magnifier so as to compensate for pincushion, barrel or
30 petzval distortion, known to those in the art.

31 The invention also provides for certain improvements in a method of manufacturing a

1 microlenslet array of the type having a plurality of lenslets formed within a optical substrate
2 having a first planar surface, a second planar surface, and a normal vector that is substantially
3 perpendicular to each surface. Specifically, the improvement of the invention includes the steps
4 of forming a first lenslet array within the first surface, forming a second lenslet array within the
5 second surface, forming a plurality of lenslet channels between the lenslet arrays wherein each
6 channel includes one lenslet from each of the arrays, the lenslet channels between at least two
7 adjacent arrays having a channel axis vector relative to the normal vector such that the cross
8 product between the channel axis vector and the optical axis vector is greater for lenslet channels
9 further away from a line extending along a center of the substrate and parallel to the normal
10 vector.

11 In another aspect, a method of manufacturing a microlens stack is provided for
12 producing a magnified image of an object along an optical axis, including the steps of:
13 combining at least two refractive lenslet arrays with at least one diffractive lenslet array to form
14 a lenslet array stack with a plurality of lenslet channels, each of the channels having a sloped
15 axis between at least two of the arrays, and arranging the channels such that the cross product
16 between the sloped axis and the optical axis is greater for lenslet channels further from the
17 optical axis as compared to lenslet channels closer to the optical axis, thereby achieving the
18 magnification selectively.

19 Such a method can include, in another aspect, the step of arranging the channels such
20 that at least two channels contribute to the image of each point of the object, providing
21 continuous imagery. The method can also include the step of arranging at least one array so as
22 to produce an intermediate image of the object and between other arrays, and inserting a field
23 stop at the intermediate image so as to reduce the field of view of at least one channel.

24 In still another aspect, a stacked array imaging system has an integral MEMS device, or
25 other electromechanical or opto-electronic actuator device, in the construction between stacks to
26 effect a variable spacing between stack elements. The MEMS or actuator increases or decreases,
27 selectively, the space between lenslets along a channel so as to change the optical conjugates
28 and thereby change the system magnification. The MEMS actuators also provide for an array of
29 electronically adjustable aperture stops or irises. The adjustable array of irises modify the image
30 properties to improve or modulate the Optical Transfer Function, to turn "on" or "off" select
31 lenslet channels, or to otherwise modify the optical transform of the object space scene into

1 image space as in optical signal processing for pattern recognition or encryption or decryption.

2 In still another aspect, a tiled array imager is provided for generating an image of an
3 object along an optical axis between the object and the image. To form the tiled array, at least
4 two stacks are arranged substantially perpendicular to the optical axis. Each of the stacks are
5 formed of a plurality of lenslet arrays including one or more non-refractive lenslet arrays and
6 one or more refractive lenslet arrays. Each lenslet array within a tiled array acts substantially in
7 concert as a single lenslet array; and the tiled arrays form a plurality of lenslet channels. Each of
8 the channels between at least two arrays has a channel axis with a predefined slope relative to
9 the optical axis. The lenslet channels further from the optical axis have a larger slope than lenslet
10 channels closer to the optical axis. These slopes providing demagnification between the object
11 and the image.

12 The invention also provides for scene generating apparatus, including: a computer for
13 generating signals representative of an selected pattern; a flat panel display responsive to the
14 signals to display the pattern, the display having a display center and a normal vector
15 perpendicular to a face of the display means; a plurality of lenslet arrays formed into a stack
16 having a plurality of lenslet channels, the channels between at least two arrays having a sloped
17 channel axis relative to the surface normal vector, the lenslet arrays being constructed and
18 arranged to generate an image of the pattern on the display means, the cross product of the
19 sloped channel axis and the surface normal vector being larger for channels further from the
20 center as compared to channels closer to the center wherein selective magnification of the image
21 is achieved.

22 In another aspect, a digital camera is provided, including: a film-formatted camera body
23 and camera lens which generate an image of a scene at an image plane within the camera body
24 and in a format corresponding to 35mm film; one or more non-refractive lenslet arrays and one
25 or more refractive lenslet arrays formed into a stack with a first outer surface and a second outer
26 surface, the stack being constructed and arranged to fit with the camera body, the lenslet arrays
27 forming a plurality of lenslet channels which act in concert to form a secondary image of the
28 camera's first image that is sized to a solid state focal plane array; and a solid state focal plane
29 array arranged at the secondary image.

30 In yet another aspect, a digital camera is provided, including: a solid state imaging
31 device of the type that includes an array of detector pixels responsive to electromagnetic

1 radiation within a range of wavelengths; a window for protecting the device and for imaging the
2 radiation onto the device, the window having one or more non-refractive lenslet arrays and one
3 or more refractive lenslet arrays formed into a stack, the stack being constructed and arranged
4 over the device and forming a plurality of lenslet channels which act in concert to form an image
5 that is sized to the device.

6 The invention also provides a compact optical correlator for imaging an object to a solid
7 state detector, including: a first stack and a second stack arranged substantially perpendicular to
8 an axis formed between the object and the detector, each stack having one or more non-
9 refractive lenslet arrays and one or more refractive lenslet arrays, the lenslet arrays forming a
10 plurality of lenslet channels wherein each channel includes one lenslet from each of the other
11 arrays, the first stack generating a Fourier image between the first and second stacks at a
12 filtering plane, the second stack generating an image of the Fourier image such that the object is
13 reimaged onto the detector; and an optical filter arranged at the filtering plane for selectively
14 filtering electromagnetic energy so as to achieve selected optical processing.

15 In one aspect of the invention, a lenslet array stack is integrated with other like lenslet
16 array stacks in a seamless tile so as to achieve a large format display. Each stack includes at least
17 one refractive lenslet array and at least one non-refractive lenslet array. The stacks are abutted in
18 a manner which achieves the size of the desired large format display; the abutted stacks thus
19 functioning, substantially, as a single stack. At the point of intersection between adjacent stacks,
20 the individual stacks provide substantially 100% fill factor; and thus the intersection is
21 substantially unnoticeable.

22 By way of example, advancements in microelectronics manufacturing technology have
23 recently produced miniature FPDs with relatively low cost, and high quality, resolution and
24 yield. These miniature FPDs typically have pixel clear aperture sizes of about twenty-five
25 microns and an overall dimension of 12.7mm by 12.7mm (standard LCD pixel sizes, by
26 contrast, are typically about two hundred and fifty microns, or one hundred dots per inch). They
27 are used, for example, within head-mounted displays for defense and commercial applications.
28 The miniature FPDs offer high optical performance and good contrast with about twenty to forty
29 lines-per-mm resolution. In accord with one aspect of the invention, an array of miniature FPDs
30 are tiled into a larger FPD of selected size. One or more lenslet array stacks are thus arranged so
31 as to reimage and magnify the tiled FPD into a large format display. In one practical aspect, the

1 stacks too are tiled. Accordingly, the tiled stacks and the tiled miniature FPDs provide a
2 convenient and efficient large format display of minimal thickness and with substantially
3 seamless effects caused by the tiling. The FPD is thus scaleable, according to the invention, in a
4 flexible, low cost, high performance assembly.

5 Lenslet array stacks of the invention can provide selective magnification, as discussed
6 herein. Like magnification stacks can also be arranged, in sequence, to achieve integer multiple
7 magnifications between an object and image. Accordingly, and in another aspect of the
8 invention, one method of the invention is to provide a magnification of $n \cdot M$, wherein n denotes
9 the number of lenslet array stacks, and where M denotes the magnification of the stack in the
10 sequence.

11 The lenslet arrays of the invention can be formed in optical grade polymer, fused silica,
12 quartz, sapphire, calcium fluoride, optical grade glass, silicon, germanium, gallium arsenic,
13 silicon carbide, zinc sulfide, zinc selenide, and other glass or crystalline materials that transmit
14 ultraviolet, visible or infrared light with low absorption and high efficiency. Certain polymers,
15 gels and other organic materials can also be used, such as bacteriorhodopsin, as known to those
16 skilled in the art.

17 The invention provides several advantages and has widely varying uses. It provides, for
18 example, hybrid diffractive-refractive optical magnifiers for use in optical display and imaging
19 systems, e.g., flat panel displays, classical cameras, and medical imagers. In one practical
20 application, the invention has beneficial use in bridging 35mm film technology to the digital age
21 by conveniently reformatting the classical image plane to the industrial sizes of the modern day
22 solid-state devices. In the realm of Fourier and/or digital systems, the invention further provides
23 a convenient forum from which to implement a variety of optical correlation or processing
24 techniques, including Fourier processing, optical computing, and data transmission methods.
25 Certain other applications, aspects and advantages are realized by the invention, including:

26 (1) Hybrid lenslet arrays (i.e., lenslet arrays made from refractive lenslets and at least one
27 array of non-refractive lenslets) of the invention can provide selective magnification of
28 miniature flat panel electronic displays. These arrays form a system that exploits the advances
29 made in microelectronic packaging and manufacturing so that high resolution active matrix
30 displays are available at high yield and low cost. Such a system further enables a large visible
31 field with a high fill factor (i.e., high throughput and "frameless" operation so that the joint

1 between adjacent stacks in a tile are unnoticeable) and yet with low overall weight, size and
2 complexity.

3 (2) Hybrid lenslet arrays according to the invention are generally scaleable such that stacks
4 of adjacent arrays perform like functions so as to provide a combined effect with reduced overall
5 manufacturing complexity. For example, a hybrid array with an achieved magnification of two
6 hundred percent can be combined with a similar array to achieve an overall object-to-image
7 magnification of four hundred percent. This obviously permits the simultaneous and simplified
8 manufacture of like arrays along a common manufacturing line, which lowers cost and which
9 increases production yield.

10 (3) Because of the high resolution and low weight provided by a system of the invention,
11 hybrid arrays of the invention are particularly suited to avionic displays; optical systems at
12 command and control centers; high definition television (HDTV); passenger, conference and
13 stadium displays; virtual conference centers; and active billboards.

14 (4) A hybrid lenslet array forming a stack according to the invention preferably has precise
15 registration along the individual lenslet channels defined by the stack transfer, transform or
16 optical radiation transfer from object space to image space. This provides accuracy in
17 characteristics of image quality, optical computing and processing.

18 (5) A stack of microlenslet arrays according to the invention can provide either
19 magnification or demagnification for a variety of specific applications.

20 (6) A stack of microlenslet arrays with a MEMS actuator device according to the invention
21 can provide electronic adjustment or tunable magnification for electronic imaging, display or
22 other applications.

23 (7) Microlenslet surface structure, according to the invention, can be (a) refractive, (b)
24 diffractive kineforms, (c) high order, high efficiency diffractive steering or focusing lenslets, (d)
25 holograms or holographic lenslets, (e) computer generated holograms, (f) effective index
26 modulating surface arrays, (g) apodizing or other spatial filters, and arrays of stops, or (h) other
27 features typically generated by lithographic and semiconductor fabrication technology.

28 (8) In accord with the invention, hybrid lenslet arrays are formed into a stack - a process
29 sometimes denoted herein as "hybridization" - of different surface types (refractive and
30 diffractive in nature) to provide excellent color, aberration or other correction for high
31 efficiency, high Modulation Transfer Function (MTF) and uniformity over a large aperture

1 optical system.

2 (9) When combined with a mechanical support structure, the input and/or output surfaces of
3 a stack provide a clear aperture which is at least equivalent to, or greater than, the mechanical
4 aperture of the support structure. This permits seamless, or "frameless," tiling of a plurality of
5 stacks into an infinitely scaleable, tiled, massive parallel processed array for very large display
6 or image acquisition over a large field of view. "Massive parallel processing," as sometimes
7 referred to herein, means the parallel addressing and control of solid state devices like the CCD
8 and frame readout for the tiled imaging or FPD projection system constructed according to the
9 invention. Massive parallel processing effects simultaneous activation or control of tile
10 elements for real-time applications (i.e., many frames per second). By way of example, if control
11 and readout electronics were serial, as opposed to parallel, then the screen or refresh rates can
12 extend an unreasonable period of several minutes.

13 (10) Microlenslet fabrication of an array of stacks, e.g., to form a tile and/or to achieve integer
14 and repeated magnification effects, permits the cost effective manufacture of large scale
15 assemblies. By way of example, massive parallel processing of discrete tile subassemblies
16 allows for cost effective computer control of large scale, seamlessly tiled array systems and at
17 very large speeds such as real-time video rates or faster.

18 (11) A lenslet array, according to the invention, can include macroscopic planar or refractive
19 lens surfaces in addition to the microlenslet surface structures. Such a lenslet array can provide
20 macroscopic radiation transfer according to a first purpose, and lenslet channel radiation transfer
21 according to a second purpose. In addition, a lenslet array of the invention can and usually does
22 include interstitial planar microsurfaces, arranged between adjacent lenslets, that do not
23 generally contribute to the overall optical throughput from the object to the image.

24 (12) In certain aspects of the invention, a stack of hybrid lenslet arrays are arranged to
25 efficiently reimage a discrete pixelated object into a discrete pixelated image. Alternatively, such
26 a stack can be arranged to image an object into a continuous image - without dark spaces, gaps
27 or blurred regions between adjacent pixels or local image areas at the image plane - by careful
28 image interlacing of adjacent channels or kernels of channels in the stacked array structure.

29 (13) Image interlacing of adjacent lenslet channels provides a uniform, high efficiency optical
30 tile system with a total optical path length or working distance which scales with the size and f-
31 number of the channels. This provides for a flat panel optical system with a thickness, weight

1 and mass that is smaller than that which is typical for a conventional macroscopic lens or mirror
2 optical system.

3 (14) The lenslet arrays of the invention can be represented by a uniform array of lenslets of
4 equal surface figure at regular spaced intervals, or by kernels of subarray lenslets of equal
5 surface figure at regular spaced intervals, or by uniquely different lenslets at regular or irregular
6 spacing. In certain aspects the lenslet arrays can be formed of lenslets with varying distance
7 from adjacent lenslets dependent upon a location from an optical or mechanical center of the
8 lenslet array surface. In yet other aspects, the lenslet arrays are arranged in a radially symmetric
9 fashion, in a manner easily defined by the Cartesian coordinate system, or in another group
10 symmetry.

11 (15) The microlenslets of the invention can have circular, square, hexagonal or other regularly
12 shaped apertures which are equal to or smaller to the lenslet-to-lenslet center spacing (i.e., so as
13 to provide a zone, between lenslets, that does not transfer radiation along a lenslet channel).
14 Nevertheless, lenslets are usually circular in shape.

15 (16) The microlenslets, the microlenslet surfaces, and/or the spaces between adjacent lenslets
16 can contain hard stops, masks or opaque zones to achieve one or more of the following: to
17 control crosstalk, to eliminate or reduce stray light, to reduce image artifacts and aberrations, to
18 maximizing image contrast, and to optimize MTF. Intra-element stops or opaque zones can be
19 fabricated by chemical modification of the lenslet array substrate material, by trench etching,
20 and by thermal or other physical processing. Surface stops can be fabricated using physical
21 deposition, chemical modification, printing or other process for depositing or placement of
22 opaque material in the interstices between lenslets. Inter-element stops can include a metal or
23 other opaque mask which also provides for accurate spacing and precision as to the location of
24 adjacent arrays in the stack.

25 (17) The microlenslets and/or spaces between adjacent lenslets can contain adjustable actuator
26 intra-element stops such as MEMS-type irises to achieve one or more of the following; to
27 control crosstalk, to eliminate or reduce stray light, to reduce image artifacts and aberrations, to
28 maximize image contrast, to improve image uniformity, to optimize MTF, and to adjust or tune
29 the system f-stop.

30 (18) A hybrid lenslet stack of the invention provides magnification or demagnification, in one
31 aspect, by outward or inward tilting of lenslets channels relative to an optical axis. In another

1 aspect, the stack can also utilize microlenslet array channels to effect magnification or
2 demagnification by outward or inward steering of individual lenslet channel axes. Further,
3 magnification (or demagnification) can be divided equally or unequally between arrays within a
4 stack, or between stacks arranged as a sequence of stacks in a single optical train. Furthermore,
5 the magnification can be adjustable using a MEMS actuator device at a location between stacks.
6 The MEMS actuator can be addressed electronically to increase or decrease the spacing between
7 stacks in order to change the optical conjugates of the imaging system.

8 (19) In the case of pixelated objects or images, individual lenslet apertures can be smaller
9 than, equal to, or larger than the pixelated dimensions of the object or image. Lenslet apertures
10 which are larger than the pixel dimensions of the object or image can have (a) fields of view
11 covering a plurality of the pixels in object or image space, or (b) a field of view which exceeds
12 the aperture of the lenslet with potential overlap among the fields of view of multiple lenslet
13 channels. Lenslets apertures that equal the pixelated dimensions in object space can (a) transfer
14 the image of many object pixels or just one object pixel, or (b) have field of view equal to the
15 lenslet aperture dimension. Lenslets with apertures that are smaller than the pixelated object
16 and/or image dimensions can utilize or interlace the images of a plurality of lenslets so as to
17 image one point in object space to one point in image space.

18 Lenslets which have an aperture that equals the field of view are the least preferred
19 configuration due to the extremely tight tolerance required in fabrication, registration, and the
20 low defect density required to achieve uniform image transfer. Lenslets with apertures that are
21 larger than the lenslet's field of view require simpler masks for fabrication with reduced features;
22 but defect densities can not be tolerated unless multiple lenslet channels are used to image a
23 single point in object space to image space. Lenslet arrays with small aperture sizes, relative to
24 the lenslet's field of view, require the most complicated masks for fabrication and the lowest
25 packing fraction for optical efficiency; but also allow for the greatest tolerance in registration
26 and defect density due to the interlacing of images from many channels from a single object
27 point.

28 (20) Hybrid lenslet array stacks according to the invention can provide inverted or erect
29 images. Systems with erect images require an odd number (i.e., 1, 3, 5, or $2n + 1$, where n is
30 an integer number) of field stops or field image surfaces internal to the stack structure. Systems
31 with an inverted image output can have either zero or an even number of field stops or field

1 image surfaces internal to the stack structure. Stacks with internal field images can incorporate
2 field stops in the form of micromachined, electro-formed, molded or other aperture plates for
3 aberration control or the improvement of image quality (e.g., MTF).

4 (21) Stacks constructed according to the invention generally include, at least, four lenslet
5 array surfaces and two substrate elements. The stack can be assembled as a stack of discrete air-
6 spaced elements with external mechanical fixturing or with mechanical spacers placed between
7 the elements and arrays. Such a stack provides a stable, monolithic structure which easily
8 integrates into a system, device or product.

9 Stack surfaces and/or spacers can include fiducial marks to facilitate micron-level
10 registration and location of components. These fiducial marks can be deposited, or male or
11 female patterns can be etched into, surfaces at interstices between microlenslets. The opposing
12 surface or fiducial mark of the next element or spacer between elements can also have fiducial
13 marks or a mating surface relief pattern to facilitate assembly and co-location of elements and
14 components of the assembly.

15 Alternatively, the lenslet apertures can be register into one or more mask plates between
16 adjacent elements of the stack to provide for co-location and precise positioning in x-, y- and z-
17 axes of the hybrid stack. Monolithic, self-alignment construction of stack assemblies allows for
18 compact, high performance optical systems with superior structural and environmental integrity
19 in comparison to conventional optical systems. Stack optics can also be assembled with buried
20 and cemented surfaces for added reliability and impermeability to contamination or dirt.

21 (22) Multi-element stack optical systems of the invention with one or more intermediate
22 image planes facilitate the insertion of passive or active media at a field image or at a collimated
23 space between two lenslets in the stack. Active media located at the field stop provides a
24 convenient forum from which to accomplish optical processing, and can include: electro-optic
25 modulators, liquid crystal light valves, active color filter mosaics, other spatial light modulators,
26 computer generated holograms, and even gain media to accommodate a wide variety of
27 applications for optical transform systems, compact optical correlators, optical network and
28 computing systems, switching systems and numerous other optical signal processors. Fixed
29 passive spatial filters, color filters, or encryption filters can also be co-located at a field image in
30 the stack assembly to create a wide variety of fixed or passive optical signal processing systems.
31 Again, the compact, monolithic nature of the stack assembly allows for ease of assembly and

1 integration with internal devices, associated electronics and mechanical fixturing.

2 (23) Multi-element stack optical systems of the invention with one or more intermediate
3 image planes facilitate the arrangement of a MEMS device or other actuator mechanism or array
4 of actuators at a field image or in the space between two adjacent stacks. The actuators can be in
5 the form of an array of moveable irises or shutters in the path of the optical channels. The irises
6 or shutter mechanisms can be used to effect an analog or digital transformation of the optical
7 signal as in an optical signal processor or encryption/decryption system.

8 (24) Stack components and assemblies can be fabricated using a wide variety of materials and
9 methods compatible with volume microelectronics assembly tooling and equipment. Substrates
10 can be semiconductor, glass, single crystal, polycrystalline, liquid crystal, polymer or other
11 optically transmissive material amenable to processing into microlenslet arrays. Metal or other
12 solid negative masters can be used for mold fabrication of hybrid lenslet arrays and stacks.
13 Hybrid arrays can also be cemented to bury surfaces for added reliability. Spacers between
14 elements can be glass, metal, polymer, crystalline or other appropriate structural or optically
15 opaque medium to facilitate registration and to enhance optical and mechanical properties.
16 Active and passive devices located between elements, particularly at field image planes, can
17 further incorporate electronics and mechanics for assembly and fixturing of stacks and lenslet
18 arrays.

19 (25) Stacks and lenslet arrays of the invention can apply to applications across the optical
20 spectrum, from the deep ultraviolet to the far infrared. Indeed, many semiconductor materials
21 that facilitate microelectronic fabrication processing have excellent infrared transmission
22 properties so as to support infrared applications. The compact, flat panel nature of the stack
23 optical system allows for easy integration with an image plane device such as a focal plane array
24 detector. The stack optics can also function as an optical signal processing window which
25 isolates and protects the FPA device in a protective atmosphere, or in a controlled environment
26 atmosphere such as cryogenic or other thermally controlled environment (e.g., heated,
27 isothermal, and non-cryogenic-cooled).

28 (26) The stack assembly, according to the invention, provides a single optical assembly for
29 use in imaging, display or detection applications using a single flat panel display, focal plane
30 array, other direct display device or detector device. The ability to fabricate stack optics with
31 nearly 100% clear aperture (relative to the mechanical size of the stack) allows for infinitely

1 scalable tiling of massive parallel processed arrays for very large flat panel displays or wide
2 area, high resolution image acquisition systems.

3 (27) In addition to the applications discussed herein, the invention is particularly well suited
4 for application with (a) massively parallel processed tiled large area FPD systems, (b) massively
5 parallel processed large area real-time medical imaging systems, (c) compact optical correlators,
6 (d) compact IR FPA imaging cameras with an integral cold stop, (e) compact CCD imaging
7 systems, and (f) optical encryption systems for security applications.

8 The fabrication of a stack or SAM assembly according to the invention has many
9 aspects, including:

10 (28) The lenslet arrays of the invention can be manufactured by molding an optical grade
11 polymer, or by coextrusion of an optical polymer, with an opaque polymer. In one aspect, the
12 mold is fabricated from a negative relief of the refractive and non-refractive lenslet surface
13 features, plus fiducial marks and mechanical assembly features. The negative relief is then
14 fabricated into a metal, ceramic or high temperature composite master, which is produced by
15 micromachining or by direct forming into the master mold material. In another aspect, the mold
16 is produced in an iterative manner by transferring a positive master in glass, semiconductor or
17 crystal material to a ceramic or elastomer template, which creates the negative mold master.

18 (29) The arrays of the invention are made from a variety of substrate materials. Depending
19 upon the wavelengths of operation, the substrates within a particular stack can be made from one
20 or more different substrate materials so as to correct for optical color or to accomplish different
21 distributions of optical power within the stack.

22 (30) Lenslet arrays of the invention can also be manufactured through replication. In this
23 aspect, a mold is fabricated from a negative relief of the refractive and non-refractive lenslet
24 microsurface features, as well as of the fiducial and mechanical assembly features. Preferably,
25 the negative relief is fabricated into a metal, ceramic or high temperature composite master,
26 which is produced by micromachining or by direct forming into the master mold material. The
27 master is thereafter coated with a release agent followed, for example, by (a) an epoxy, (b) a
28 polymer, (c) an optical quality organic, or (d) a sol gel material to produce a thin sheet of
29 material with lenslet array features, fiducial marks, and mechanical assembly features to
30 facilitate transfer and bonding to a flat optical substrate. The bulk optical substrate can
31 additionally include opaque interstitial areas or masks to provide for stops and to eliminate or

1 reduce optical crosstalk among nearby lenslet channels.

2 (31) Fabrication of lenslet arrays according to the invention can beneficially utilize substrates,
3 equipment and process technology common to semiconductor microelectronic lithography.
4 These semiconductor processes can include deposition and photoresist mask generation to
5 facilitate the fabrication of surface features, the modification of the index of refraction, and the
6 application of physical masks. Reactor processes common to semiconductor processing are also
7 used, in other aspects, for chemical etching, reactive ion etching, plasma etching, physical vapor
8 deposition, chemical vapor deposition, epitaxial growth, ion implantation, electron beam
9 deposition, and other radiation exposure and activation processes to form refractive and non-
10 refractive lenslet arrays with the selected substrate material.

11 (32) The interstitial regions between lenslet channels are preferably coated with an opaque
12 material - such as metal, ceramic or oxide - using semiconductor microelectronic processes,
13 particularly the reversal of the photomask resist process described above.

14 (33) In a preferred aspect of the invention, the masks used to fabricate the lenslet arrays
15 include fiducial features, which facilitate alignment and registration of lenslet array channels in
16 cartesian x-y and rotational coordinates. The fiducials are either located outside of the lenslet
17 clear aperture or interstitial to the lenslet array features. These fiducials can be clear with an
18 opaque background, or opaque in a transparent background.

19 (34) The fiducial features of the invention can frame the entire lenslet array mask, or parts of
20 the lenslet array mask, or within interstitial regions to the lenslet array channels. Fiducials can be
21 horizontal or vertical lines, sequences of lines, crossed lines, circles, squares, hexagons, other
22 geometrics or combinations of geometric shapes.

23 (35) Generally, the fiducial markings facilitate the manufacture of precise registration of
24 photomasks and lenslet stacks by co-alignment and/or registration. The markings can also create
25 optical effects to assist in this assembly process. For example, precise alignment of the marks
26 within a substrate and relative to a side-to-side arrangement of arrays can be made to produce
27 optical effects such as a Moire pattern or other interference effect so as to indicate proper
28 registration.

29 (36) In a preferred aspect of the invention, lenslet array substrates are fabricated with
30 additional fiducial marks, or surface relief features (etched below the surface or protruding
31 above the plane of the lenslets) to facilitate stack assembly. In particular, these fiducials can be

1 used to assist in the alignment of elements such as mechanical spacers between adjacent arrays,
2 or in the positioning of stops or optoelectronic devices at an intermediate image plane. Their
3 placement can be outside, or interstitial to, the array's clear aperture; and their shape can be in
4 the form of lines, crosses, dots, rectangles, squares or other geometric features that permits
5 visual or machine-aided alignment of stack elements. The fiducials can further facilitate
6 mechanical pinning or interlocking of adjacent stack elements.

7 (37) In one convenient aspect of the invention, fiducial marks and assembly features are
8 fabricated of metal or other target materials used in the masking of the interstitial and
9 surrounding regions of the lenslets. In another aspect, the fiducial marks and assembly features
10 are etched into the substrate. In yet another aspect, the fiducial marks and assembly features are
11 fabricated onto mechanical spacers and other devices for placement within the stack.

12 (38) Fiducial marks and assembly features can be formed of solder, thermoset or other
13 material that transforms from a solid to a liquid when subjected to heat or other activation such
14 that a surface tension is created to promote alignment of the stack. The subsequent
15 transformation of the fiducial and assembly features back to a solid thereby bonds the stack
16 together into a monolithic structure.

17 (39) The stack can include lenslet surfaces that are immersed in an adhesive for monolithic
18 bonding of the SAM.

19 (40) Stack assembly with micromechanical and electronic parts is greatly facilitated by visual
20 or machine-aided tooling such as a microscope or other imaging devices. Typically, these
21 devices have sufficient magnification to view the fiducial alignment microfeatures so as to
22 facilitate precise array positioning in x, y and rotational coordinates.

23 (41) In another aspect, anaerobic, thermoset, room temperature adhesives or other bonding
24 agents are used to assemble the stacks at the edges or at internal locations within the stack.

25 (42) Mechanical spacers and surface alignment features can include a gel, thermoset or a
26 solder which bonds the stack together when activated at the point of proper registration.

27 (43) Stack alignment features can include thru-holes - at the edge of the stack's clear aperture
28 or at interstitial locations relative to the lenslet channels - so as to provide for the insertion of
29 micromechanical pins which assist stack assembly and which mechanically tie the stack into a
30 monolithic structure.

31 (44) A substrate can include features which are designed into its outer surfaces to facilitate

1 the assembly of the SAM relative to external mechanical mounts or housing structure. Further,
2 such features can assist in the alignment and placement of an array relative to an imaging device,
3 detector, or display device, e.g., a LCD. They can also facilitate assembly of a seamless tiled
4 array construction of SAMs into a massive parallel processing system.

5 In another aspect, the invention also concerns a hybrid, refractive/diffractive, stacked
6 optical lens array imaging system that transmit a two-dimensional image from an object plane to
7 an image plane. Specifically, the imaging system utilizes a stack of arrays of lenses, each array
8 comprising a plurality of small apertured lenses ("microlenses" or "lenslets"). The optical
9 imaging system includes micro-optics with a relatively short focal length and high optical
10 efficiency and high resolution for imaging with or without magnification or demagnification.
11 The optics thus form a "stack" of a plurality of hybrid (i.e., refractive, diffractive, etc.) lenslet
12 arrays.

13 The system can provide for finite conjugate imaging or infinite conjugate imaging, and
14 can contain at least one or more intermediate field images with an erect or inverted image at the
15 overall system output image plane. The system can further reimage a pixelated object space to a
16 discrete array image space. The system can also reimage a continuous object to a continuous
17 image without dark spaces, gaps or blurred regions between pixels or image areas at the image
18 plane.

19 Furthermore, the optical conjugates and continuous or discrete imaging properties of the
20 system can be fixed or adjustable. Placement of one or more MEMS devices or other
21 electromechanical actuators between lenslet stacks provides for increasing or modulating the
22 spacing between stacks to effect a change in optical conjugates for the system. Alternatively, an
23 array of MEMS irises or shutter devices can adjust the uniformity or continuity of a continuous
24 or pixelated image.

25 Each array of lenslets may incorporate integral hard stops (such as chrome baffles) or
26 opaque zones between lenslets for control of crosstalk, for minimization of stray light, and for
27 maximization of image contrast and the modulation transfer function. A key aspect of the system
28 is the interlacing of images from adjacent lenslet channels so that multiple lenslet channels may
29 contribute to reimagining a point or pixel in object space to a corresponding point or pixel in
30 image space. The effective f-number of the system is therefore smaller than the f-number of a
31 single lenslet channel. The thickness of the system is a function of lenslet size, f-number and

1 optical lens material, and is, therefore, substantially thinner than an equivalent optical system
2 using large aperture macrolenses.

3 The stack of lenslet arrays can be configured and assembled within a monolithic
4 structure for simplicity of construction and alignment. The image interlacing property of the
5 system accommodates a large tolerance for lateral misalignment due to the contribution of
6 multiple lenslet channels to the complete, continuous image.

7 The number of lenslets in each array stack can be greater than, equal to, or less than the
8 total number of pixels in object or image space. Magnification can be divided equally among the
9 lenslets or in various portions between the optical stack before and after the field stop array.
10 Individual lenslets or entire lenslet arrays can be tilted inward or outward for magnification or
11 demagnification. Lenslet arrays can be formed on planar substrates or can be hybridized with
12 macrolens substrates. The lenslet surface figures can be constant over one array surface with
13 uniform spacing. In the alternative, the surface figures can be arranged in kernels of n by m
14 lenslets of constant figure or with changing figure in the adjacent kernels of lenslets. Or, the
15 surface figures can vary step-wise across the entire aperture of the stack such that every lenslet
16 has a unique figure unto itself.

17 The field stop array can incorporate either an array of reticles, a spatial light modulator, a
18 MEMS actuator, other electromechanical actuator mechanisms, or other passive or active optical
19 systems or media. The lenslets can be refractive, diffractive, holographically generated, or
20 gradient indexed. The value of hybrid lenslet arrays is for chromatic correction, aberration
21 correction or possible encryption to produce a desired corrected or processed image at the image
22 plane.

23 The excellent uniformity of optical throughput and image quality across the entire clear
24 aperture of the system at the image plane output allows for fabrication of "tiles" of the stacks
25 with optics to the edge for 100% clear aperture. The tiles can be integrated into a very large,
26 infinitely scaleable imaging or display system in a seamless fashion. For example, in one aspect,
27 a large, high resolution, flat panel electronic wall display is formed using a plurality of small
28 liquid crystal displays ("LCDs"), miniature flat panel displays ("FPDs") or other compact
29 displays, magnified and imaged through a mosaic array of tiles. In another example, an ultra-
30 high resolution, large area, charge coupled device ("CCD") medical X-ray imaging system is
31 formed by tiling stacks with X-ray phosphor screen inputs to small, low-cost, high-speed CCD

1 camera outputs. Massive parallel processors ("MPPs") integrated within a high speed computer
2 system permit video rate, real-time, or other high frame and data rate transfer of an image in the
3 case of the medical X-ray system, or active display in the case of the wall display.

4 The invention is next described further in connection with preferred embodiments, and it
5 will become apparent that various additions, subtractions, and modifications can be made by
6 those skilled in the art without departing from the scope of the invention.

7

8 Brief Description of the Drawings

9 A more complete understanding of the invention may be obtained by reference to the
10 drawings, in which:

11 FIG. 1 shows a cut-away side view of a stacked array magnifier constructed according to
12 the invention.

13 FIGS. 1A and 1B show, respectively, front and back views of the stacked array magnifier
14 of Figure 1;

15 FIG. 2 shows a system constructed according to the invention and which includes a five
16 array stack for imaging an object onto a CCD array;

17 FIGS. 2A and 2B illustrate representative techniques of the invention used to separate
18 adjacent arrays to obtain selected separation distances as well as coregistration;

19 FIG. 3 illustrates multiplicative magnifications achieved through a plurality of
20 magnifying stacks constructed according to the invention;

21 FIG. 4 illustrates an arrangement of stacks formed into a tile to provide a large format
22 display according to the invention;

23 FIG. 5 illustrates one stack constructed according to the invention and which includes
24 both microlenslets and macrolenslet structure;

25 FIGS. 6A-6B illustrate selected types of imaging according to the invention, including
26 continuous and pixelated imaging;

27 FIGS. 7-7E illustrate selected options of arranging microlenslet patterns in an array,
28 according to the invention;

29 FIGS. 8 and 8A show other techniques of imaging an object with magnification,
30 according to the invention, and with tilted lenslets or lenslets with varying optical power within
31 the stack arrays;

1 FIGs. 9 and 9A show a sequence of stacks providing a relay of images to achieve erect or
2 inverted images, selectively, and to stop the internal images so as to improve image quality;

3 FIGs. 10A-10C show, respectively, holographic lenslet manufacture, a representative
4 holographic lenslet, and a resulting operation of such a holographic array, in accord with the
5 invention;

6 FIGs. 11A-11B show, respectively, phase modulation lenslet manufacture and a resulting
7 operation of a phase modulation array, in accord with the invention;

8 FIGs. 12A-12C show, respectively, index modulating lenslet manufacture, a
9 representative gradient index lenslet, and a representative Gaussian-shaped index lenslet, in
10 accord with the invention; and FIG. 12D shows an alternative index modulation lenslet
11 manufacture utilizing nanometer-sized substrate cuts;

12 FIGs. 13A and 13B illustrate, respectively, a negative mold and a lenslet array made
13 from the mold, in accord with the invention;

14 FIGs. 14A and 14B illustrate lenslet structures made from diffractive kineforms;

15 FIGs. 15A-15G illustrate different lenslet constructions according to the invention;

16 FIG. 16A-16C illustrate different lenslet FOVs relative to an RGB object, in accord with
17 the invention;

18 FIG. 17A-17B illustrate how lenslet FOV impacts image defects;

19 FIG. 18 shows a cut-away side view of a stack assembly constructed according to the
20 invention and including spacers, fiducials, assembly pins, opaque stops at the interstitial spacing,
21 actuators and MEMS devices, and associated items;

22 FIG. 19 illustrates a Hartman Transform encoder constructed according to the invention;

23 FIG. 20 illustrates optical processing apparatus constructed according to the invention;

24 FIG. 21 illustrates a scene generation system constructed according to the invention;

25 FIG. 22 shows a digital camera constructed according to the invention, including a solid
26 state display and a stack for converting a 35mm film image to the solid state display;

27 FIG. 23 is a schematic view of a four element stack of the present invention;

28 FIG. 24 is a schematic view of a four element stack, similar to that of FIG. 23,
29 incorporated into an embodiment for magnification of light emitted from a miniature flat panel
30 display, in accord with the invention;

31 FIG. 25 is a schematic diagram of the system of FIG. 24 incorporated into a computer-

1 controlled, multi-stack embodiment of the invention;

2 FIG. 26 is a schematic view of a four element stack, similar to that of FIG. 23 and FIG.
3 24, incorporated into an embodiment of the invention for demagnification of X-rays to a charge
4 coupled device;

5 FIG. 27 is a schematic diagram of the system of FIG. 26 incorporated into a computer-
6 controlled, multi-stack embodiment of the invention;

7 FIG. 28 is a schematic view of a four-element stack, similar to that of FIG. 23, FIG. 24
8 and FIG. 26, incorporated into an embodiment of the invention for adjustable magnification
9 and/or focus adjustment with a stack of MEMS actuators;

10 FIGs. 28A and 28B illustrate representative techniques of the invention used to modify
11 the spacing between adjacent arrays to obtain selected separation distances in order to change
12 the magnification, focus or defocus the optical system; FIG. 28C shows a side view of the
13 MEMS of FIG. 28B;

14 FIG. 29 is a schematic view of a four element stack, similar to that of FIG. 23, FIG. 24,
15 FIG. 26 and FIG. 28 incorporated into an embodiment of the invention for an array of adjustable
16 MEMS irises or shutters in the optical path of lenslet channels;

17 FIGs. 29A and 29B illustrate representative techniques of the invention used to actively
18 shutter discrete lenslet channels or to actively modify the f-stop of discrete lenslet channels or an
19 optical system; FIG. 29A-1 shows a side view of the MEMS of FIG. 29A; and FIG. 29B-1
20 shows a side view of the MEMS of FIG. 29B.

21

22 Detailed Description of the Drawings

23 FIG. 1 shows cut-away side view of a stacked array magnifier 10 constructed according
24 to the invention. The "stack" of FIG. 1 is made from two substrates 12 and 14 held together by
25 an opto-mechanical fixture 16. Each of the substrates 12, 14 has at least one microlenslet array
26 18 disposed therewith. As illustrated, for example, substrate 12 provides two arrays 18a, 18b;
27 while substrate 14 provides two arrays 18c, 18d. Each of the arrays 18 is made up of a plurality
28 of microlenslets 20, the physical features of which are described in more detail below. Briefly,
29 however, there are at least two types of lenslets 20 in the magnifier 10: refractive lenslets and
30 non-refractive lenslets. As illustrated, for example, array 18a and array 18d are made up of
31 refractive lenslets 20a and 20d, respectively. Array 18b and 18c, on the other hand, are made up

1 of non-refractive lenslets 20b and 20c, respectively. Typically, the non-refractive lenslets are
2 made up of diffractive gratings which include blazed grating microfeatures.

3 The magnifier 10 of the illustrated embodiment operates to form an image 22 of the
4 object 24 along an optical axis 26 (note for purposes of illustration that the object "H" of FIG. 1
5 is shown sideways to the imaging axis when, in reality, it would need to face the magnifier 10 in
6 order to be reimaged).

7 The lenslets 20 of the arrays 18 make up a plurality of channels 28 (for clarity of
8 illustration, only two channels are illustrated with a dotted line indicating the optical path along
9 the channel). In order to provide a magnification in the illustrated embodiment of FIG. 1, some
10 of the channels are sloped relative to the optical axis 26 and between at least two of the arrays
11 18. By way of example, the slopes of the channels 28 between arrays 20b and 20c vary as a
12 function of the channel's distance from the axis 26: the slope of channel 28a - which is further
13 from the optical axis 26 - is greater than the slope of channel 28b, which is closer to the optical
14 axis. Accordingly, the light radiation between the object 24 and image 22 is "spread out" to
15 achieve the desired magnification.

16 The details of the magnification and imaging process, according to the invention, are
17 described in more detail below. However, it should be apparent that each of the channels images
18 points of the object 24 to points in the image 22. For example, channel 28b images point 30 of
19 object 24 to point 32 in image 22; while channel 28a images point 34 of object 24 to point 36 in
20 image 22. The spacing between lenslets 20 and the optical character of the lenslets along each
21 channel determines the individual field of view of each channel 28. As will become more
22 apparent below, the channel field of view can overlap with other channels to provide a
23 continuous image, such as shown in FIG. 1.

24 Those skilled in the art should also appreciate that the imaging properties of the
25 magnifier 10 permit a similar demagnification of objects by inverting the magnifier 10. If, for
26 example, the image 22 is the "object," then the magnifier 10 will generate an "image" 24 which
27 is a demagnified version of the "object."

28 FIGs. 1A and 1B illustrate, respectively, front and back views (not to scale) of the
29 magnifier 10. Specifically, Figure 1A is a view of the magnifier 10 as viewed from the position
30 of the object 24; while Figure 1B is a view of the magnifier 10 as viewed from the position of
31 the image 22. As easily seen, the spacing between the various lenslets 20 is greater within FIG.

1 1B as compared to the spacing between the lenslets of FIG. 1A, which is a result and a function
2 of the desired magnification. Although not necessary, the lenslets 20a of array 18a are illustrated
3 as being smaller than the lenslets 20d of array 18d in proportion to the magnification desired
4 between the object 24 and image 22. Usually, and similar to conventional optical lens trains,
5 lenslets of the several arrays are made with identical diameters to accommodate mechanical
6 microfeatures. However, because channels can be tilted (as described herein), inadequate
7 allowance in the interstitial spacing can result in crowding of lenslets at one of the surfaces.
8 Accordingly, the design of a stack such as stack 10 should properly consider a balance of light
9 collection or transfer efficiency (i.e., the maximum lens transmitting area or open area ratio
10 through the arrays) while accommodating the lenslet channel spacing of all the arrays. By way
11 of example, if the last surface - e.g., array 18d - has very small apertures spaced widely apart,
12 then it is possible to accommodate a large magnification with close spacing of lenslets at the
13 first surface - e.g., array 18a. However, the low open area ratio of the second surface will result
14 in a low optical efficiency, similar to the effect of stopping down a conventional camera (which
15 is good for high speed applications but only if there is good lighting, e.g., a flash lamp).
16 Typically, the lenslet sizes are between about $5\mu\text{m}$ and $1000\mu\text{m}$.

17 In FIGs. 1A and 1B, the area illustrated with diagonal lines (denoted in the figure as
18 "interstitial planar microsurface) and between the several the lenslets 20 is generally planar and
19 does not function to image radiation between the object 24 and image 22. Rather, the energy
20 which impinges between lenslets 20 is preferably blocked so that such radiation does not reach
21 the image plane (i.e., the plane at which image 22 resides). As described below, baffling, stops,
22 masking and other optical techniques are used to prevent this unwanted radiation transfer. In one
23 example, the interstitial planar surface is itself coated to be optically opaque to the desired
24 radiation transmitted between the object 24 and image 22. In other examples, the opaqueness
25 between lenslets can be fabricated by chemical modification of the lenslet array substrate
26 material, by trench etching, and/or by thermal or other physical processing. Surface stops
27 forming the opaqueness can also be fabricated using physical deposition, chemical modification,
28 printing or other processes.

29 Stops such as a field stop or a Lyot stop can also be inserted at or near to an internal
30 image to reduce cross-talk or other stray radiation that might scatter from various surfaces or
31 which might transmit through the interstitial surfaces. With further reference to FIG. 1, for

1 example, the stops 25 are arranged at an intermediate image plane 27 within the stack (note that
2 at least one intermediate image is required to achieve an upright image 22). Those skilled in the
3 art will appreciate that the purpose of a field stop, generally, is to restrict the field of view; while
4 a Lyot stop is used generally to limit the transmission of unwanted diffraction effects. These
5 inter-lenslet stops 25 can include a metal or other opaque mask which also provide for accurate
6 spacing and precision as to the location of adjacent arrays 18 in the stack. They further can be
7 arranged into a single structure such as a flat metal disc that is mounted to within the fixture 16
8 via a male/female connection 29 into the fixture 16. Note, for clarity of illustration, that only two
9 stops 25 are shown when it is intended that many or most of the channels 28 have corresponding
10 stops 25 located at the image plane 27.

11 Generally, at least four arrays of lenslets and at least two substrates are used to form a
12 stack according to the invention. FIG. 2, for example, illustrates one simple use of the invention:
13 a four substrate stack of five arrays imaging an object 38 onto a solid state device such as a CCD
14 array 40. CCD electronics 42 and known to those skilled in the art transfer the charge data from
15 the CCD array 40 to a computer 44 with a display screen 46 so that the object's image 48 is
16 viewable on the screen 46. In this illustration, all of the channels 50 are substantially parallel to
17 the optical axis 52 such that unit magnification is achieved (i.e., unit magnification means a
18 magnification of "1").

19 With further reference to FIG. 2, a stack 53 is made of four substrates 54a-54d that each
20 have one or more arrays of lenslets 56 added thereto (note, for clarity of illustration, that only
21 four lenslets are shown per array while in reality many lenslets exist for each array). Substrate
22 54a has one array disposed internally to the substrate material, which is typically made from
23 semiconductor material, glass, single crystal, polycrystalline, liquid crystal, polymer or other
24 optically transmissive material amenable to processing into microlenslet arrays. In one example,
25 the lenslet 56a of the array within substrate 54a is made through ion doping to achieve a
26 refractive effect, such as discussed in connection with FIGs. 11 and 12. Substrate 54b and
27 substrate 54c each provide an array of non-refractive lenslets 56b and 56c, respectively, that are
28 made onto the surfaces of the substrates 54a, 54b. Substrate 54d has two arrays formed onto
29 each of its surfaces: an array of non-refractive lenslets 56d on one surface of the substrate 54d
30 and an array of refractive lenslets formed onto the other surface of the substrate 54d.

31 FIG. 2 also illustrates other methods of mechanically holding the substrates 54 and

1 arrays lenslets 56 into the stack 53. Like in FIG. 1, one method for holding the arrays together is
2 with an opto-mechanical fixturing 58 attached to the edges 60 of the substrate arrays 54.
3 However, the arrays can also be separated by spacing elements 62. In one embodiment of the
4 invention, fiducial marks 63 are made onto one or more of the surfaces (through deposition or
5 other methods known to those skilled in the art of microlenslet manufacture) so that the elements
6 62 can be properly placed between the interstitial spacing between the lenslets. Such spacing
7 elements 62 can further support the accurate coregistration of adjacent arrays, such as illustrated
8 in FIGs. 2A and 2B.

9 FIG. 2A illustrates portions of two substrates 64 and 66 separated by spacing elements
10 68. Not only do the spacing elements 68 provide proper distancing between the arrays 70a, 70b,
11 formed by the lenslets 72a, 72b, respectively; but they also provide for proper coregistration
12 between lenslets 72 within any given channel 74 since the female etch patterns 76 are accurately
13 applied to the substrates 64, 66 prior to assembly of the stack. Spacing elements 68 can be fixed
14 passive structures or an active stack element consisting of electromechanical actuator
15 mechanisms or MEMS devices. The active stack element can include circuitry and edge
16 connections for electronic address of actuator mechanisms in order to expand or contract the
17 spacing between lenslet arrays.

18 FIG. 2A also illustrates one non-refractive lenslet 72b constructed according to the
19 invention. The lenslets 72b are microelements which form an array of blazed gratings. Those
20 skilled in the art should appreciate that blaze gratings have angled grating grooves 73 that are
21 optimized, in angle and as a function of wavelength, so as to diffract light energy into highly
22 efficient orders and in the direction of choice. The grooves 73 can be tilted at an angle θ , for
23 example relative to the substrate surface 66a, so as to achieve the desired optical energy transfer.
24 Representative designs according to the invention are described in more detail below.

25 The combination of a non-refractive lenslet 72a and non-refractive lenslet 72b in a stack
26 is sometimes denoted herein as a "hybrid" lenslet array. In particular, a stack of different lenslet
27 arrays is a hybridization between refractive and non-refractive lenslets to achieve improved
28 optical properties such as reduced color or other optical aberrations, enhanced throughput
29 efficiency, high resolution or MTF, and field uniformity.

30 FIG. 2B illustrates yet another embodiment of aligning adjacent arrays in a stack. In
31 particular, FIG. 2B shows partial substrates 78, 80 with partial arrays of lenslets 82, 84 spaced

1 apart by male and female etch patterns 86, 88, respectively, formed into the substrate surfaces.
2 Note that in FIG. 2B the two adjacent arrays of lenslets are all refractive elements, which is yet
3 another reasonable and expected lenslet configuration according to the invention.

4 FIG. 3 shows a sequence of three stacks 90 arranged into an optical system 92 to provide
5 a magnified image 94 of an object 96. By way of example, each of the stacks 90 can be made
6 similar to the magnifier stack 10 of FIG. 1. Typically, a stack according to the invention
7 provides at most an 8:1 magnification ratio. However, stacks can be arranged in sequence to
8 boost the overall magnification significantly, such as shown in FIG. 3. If, for example, each of
9 the stacks 90 provides a magnification of 2:1, then the sequence of stacks 90 of FIG. 3 provides
10 a magnification of 2^3 , for a total magnification of 8:1 for the system 92. As above, one technique
11 for keeping the array of stacks together is through an opto-mechanical end piece 94. However,
12 inter-stack spacers 96 can also be used alone or in conjunction with the piece 94. The spacers 96
13 can be made similarly to the spacers 62 of FIG. 2, and including the various arrangements set
14 forth in FIGs. 2A and 2B. Like above, the achievement of precise coregistration between lenslet
15 arrays is advantageous in improving image quality and processing capability.

16 It is not necessary, however, that each of the stacks 90 of FIG. 3 have the same
17 magnification. Rather, stacks of different magnification can be arranged in sequence to provide a
18 multiplying magnification effect. In addition, magnification limitations of 8:1 are dependent
19 upon many practical factors relating to lenslet spacing, open area ratios, lenslet powers, and
20 other fabrication and assembly issues. Those skilled in the art should appreciate that the 8:1 ratio
21 will increase with improvements of microlithography, lenslet processing, and micromachining
22 and microalignment.

23 One clear advantage of the system 92 of FIG. 3 is that each of the stacks 90 can be made
24 separately and similarly along a common production line, thereby simplifying the complexity of
25 the overall system 92, improving production yields, and reducing non-recurring costs needed to
26 tool-up for the desired opto-mechanical configurations.

27 FIG. 3 also shows the f-number differences between the overall system 92 and an
28 individual channel 96. Note for clarity of illustration that only one channel 96 is illustrated, with
29 associated lenslets 98; while in reality there are many similar channels arranged throughout the
30 stacks 90. In addition, the lenslets 98 are grossly oversized in comparison with reality, also for
31 clarity of illustration. It is clear with reference to FIG. 3 that the overall f-number of the system

1 92, illustrated by the cone angle 100, is less than the f-number of the channel 96, as indicated by
2 the cone angle 102. Accordingly, the f-number of the channels 96 is less than the f-number of
3 the system 92. Those skilled in the art should appreciate that an f-number of about $f/1$ is
4 desirable in view of energy throughput; and therefore many systems strive for similar low f-
5 numbers. As a result, individual channel f-numbers are typically greater than about $f/1$.

6 FIG. 4 shows a perspective view of an imaging system 104 made from tiled array of
7 stacks 106 that are formed together into a two functional stacks 108a, 108b. It is sometimes
8 difficult to manufacture a single stack at desired large physical dimensions. Accordingly, stacks
9 can be tiled together to the desired display format. As above, they can also provide selected
10 magnification to achieve the desired display size and characteristics. By way of example, a stack
11 of the invention can be used to provide a large format display of a miniature FPD 110. The
12 miniature FPDs of the prior art have very high quality and resolution; but they are too small for
13 comfortable viewing. Thus, even though the object 112 on the FPD 110 is good; it is too small
14 for viewing by an audience spaced away from the display 110. Accordingly, the system 104
15 reimages the display 110 (and particularly the object 112 on the display 110) to the front 114 of
16 the system 104 (see the image 116 of the object 112). In this manner, a user (here shown as a
17 human eye 118) can comfortably view the image 116 as opposed to the object 112 on the FPD
18 110.

19 Because the lenslets (not shown) of each of the stacks 106 are so small and because they
20 extend substantially to the edge of each stack, the junctures 120 between the separate stacks are
21 substantially invisible to the user 118. That is, the lenslets can provide substantially 100% fill
22 factor of the physical size of the stack; and therefore the joinder of two or more stacks in a tile -
23 such as illustrated in FIG. 4 - is practically invisible or "frameless." Accordingly, the tiling
24 process described in FIG. 4 is scaleable to the desired physical configuration of the overall
25 display 104. In the case of massively parallel processing, the tiled stacks are arranged in a
26 pattern that is adequate to accommodate the data being processed.

27 Irregardless of the fill factor, each of the channels passing through the stacks 106 has a
28 selected field of view (FOV). If desired, the FOV of each channel can be overlapping with at
29 least one other channel so that a continuous image is obtainable. This overlapping FOV
30 additionally helps mask the junctures 120 from the user 118. The overlapping FOV effect is
31 sometimes referred to herein as "image interlacing" whereby each point on the object is

1 reimaged by a plurality of channels so as to ensure a continuous image, such as shown in FIG. 1.

2 Because the arrays of the invention can have very high fill factors relative to the physical
3 dimension of the stack, it is typically the mechanical support structure which limits the overall
4 aperture of the stack. By way of example, and with reference to FIG. 3, it is generally the clear
5 aperture 95 of the structure 94 which limits the aperture of the system 92 and not the combined
6 FOV of the lenslet arrays with the substrates.

7 FIG. 5 shows one embodiment of the invention wherein a stack 122 constructed
8 according to the invention includes both arrays of microlenslets 124, at least one macrolens
9 surface 126, and one or more substrates 128. Opto-mechanical fixturing 130 supports the stack
10 and holds the arrays in alignment. The purpose of the macrolens surface 126 is to provide
11 continuous and relatively large optical power to radiation passing therethrough so as to achieve a
12 desired optical result. Lenslets 124 can be made with the macrolens surface 126, as shown, or
13 the macrolens can be free-standing and without lenslets therewith. In at least one of the arrays of
14 lenslets 124 is non-refractive in nature, such as illustrated by the lenslets 124a on the substrate
15 128a. Accordingly, the microlenslets 124 of FIG. 5 generally have a first purpose directed at
16 microimaging features of the radiation transfer; while the macrolens 126 has a second purpose
17 directed at macroimaging features of the radiation transfer.

18 FIGs. 6A-6B illustrate various types of imaging achievable with a system constructed
19 according to the invention. In FIG. 6A, a stack 132 is constructed with arrays of microlenslets
20 134 and channels 136, such as described above (note, as before, that only a few of the
21 microlenslets 134 and channels 136 are shown for clarity of illustration). The object in this
22 figure is a pixelated object array 138 such as a computer display screen, containing a plurality of
23 light emitting pixels 140. Even though the entire stack 132 operates to provide an image 142
24 (here shown with slight magnification, though not required) of the array 138, each individual
25 channel's FOV is limited to the pixelated dimensions of the computer display pixels 140 such
26 that there is a one-to-one correspondence between lenslets 134 and pixels 140; and that there is
27 no overlapping between channels 136 so that no two channels 136 reimage the same pixel to the
28 image 142.

29 The arrangement of FIG. 6A is useful for example when it is important to restrict the
30 cross-talk between adjacent pixels. As shown, the image 142 is easily converted to electrical
31 signals by a CCD array since the image 142 is also pixelated, magnified, and discrete with a

1 one-to-one correspondence with the pixels 140.

2 Those skilled in the art should appreciate that the FOV of each channel can thus be
3 arranged to cover less than the x, y pixel dimensions of the array 138. This might be used, for
4 example, to greatly limit the effects of cross-talk and scatter between adjacent channels and to
5 compensate for diffraction effects.

6 FIG. 6B, on the other hand, illustrates image interlacing such that each point 144 on the
7 object 146 is reimaged to corresponding points 144' at the image 152 by at least two channels
8 148 of the stack 150. For clarity of illustration, only two channels 148 are shown in the stack
9 150, each channel having at least one refractive lenslet 153a and at least one non-refractive
10 lenslet 153b; and only two channels 148 are shown to reimage each point 144 of the object 146
11 to the image 152. Typically, many more channels 148 reimage each point 144 in the object 146.
12 In this manner, the image 152 is "interlaced" with microlenslet reimaging from many channels
13 148; thereby ensuring that there are no gaps in the image, even if a channel 148 is damaged or
14 inoperative.

15 FIGs. 7A-E illustrate various arrangements of lenslets within a lenslet array such as
16 described herein. For purposes of illustration, the arrays of FIGs. 7A-7E are shown from a view
17 that is substantially perpendicular to the face of the array, such as along the optical axis 26 of
18 FIG. 1. Briefly, FIG. 7A shows an array 160 of lenslets 162 arranged at regularly spaced - e.g.,
19 Cartesian - intervals 164 along the array surface 166. FIG. 7B similarly shows a kernel array
20 168 of lenslets 170 with selected distances 172 between lenslet kernels 168 (i.e., a kernel in this
21 instance refers to a sub-array pattern that is repeated throughout the array in a similar or different
22 pattern). The arrangement of FIG. 7B is useful, for example, in providing multiple imaging
23 systems on a common array substrate 174. FIG. 7C shows an array of lenslets 176 that are
24 irregularly spaced from each other in unique or semi-unique form along the array surface 178.
25 Note that FIG. 7C also illustrates that lenslets can have varying shapes, according to the
26 invention, such as circular, hexagonal, square, triangular, trapezoidal, and rectangular. As above,
27 the interstitial spacing 180 between lenslets 176 are opaquely covered or stopped via optical
28 techniques, so as to reduce or eliminate radiation transfer through the regions 180. Note also
29 that the shape of the array substrates are a matter of design choice, such as circular as in the
30 substrate 166, 174 of FIGs. 7A and 7B, and rectangular as in the substrate 178 of FIG. 7C, so as
31 to fit with a selected opto-mechanical assembly or system. FIG. 7D illustrates an array of

1 lenslets 182 that are arranged in a radial fashion; while FIG. 7E illustrates lenslets 184 that are
2 arranged with varying distances from the center 186 of the array 188. The configuration of FIG.
3 7E is one used often, in accord with the invention, to achieve selected magnification in an
4 image, similar to the technique shown in FIG. 1, so that a given channel can spread outwards
5 relative to the optical axis. Note in FIG. 1 that while the lenslets 56 extend in varying distances
6 from the axis 26, the pattern need not be radial such as shown in FIG. 7E.

7 Those skilled in the art should appreciate that the lenslet sizes, and the number of
8 lenslets, within the arrays of FIGs. 7A-7E are shown for illustrative purposes and are not to
9 scale. In reality, the lenslets of these figures are much smaller as compared to the substrate size;
10 and there are typically many thousands of lenslets within a given array.

11 FIG. 8 illustrates a stack 190 with microlenslets 191 arranged in a tilted manner, relative
12 to the optical axis 192 between the object 194 and the image 196, so as to achieve selected
13 demagnification. The effect is similar to FIG. 1 except that the lenslets 191 themselves are tilted
14 relative to the axis 192; while the channels 200 are substantially parallel to the axis 192. This
15 tilting of lenslets inwards and outwards provides for selected magnification of the stack 190.
16 However, problems associated with tilting lenslets as in FIG. 8A include fabrication and process
17 limitations. Diffractive steering lenslets generally operate better. Nevertheless, diffractive
18 surfaces can be micromachined (or processed) so as to "blaze" the overall array surface so as to
19 produce macroscopic Fresnel-like surface kineforms and to provide tilted substrate regions prior
20 to lenslet formation. This facilitates the tilting of lenslets as in FIG. 8A. Note also that tilted
21 lenslets and sloped lenslet channels can be combined together in a stack to achieve other varying
22 effects such as magnification.

23 In an alternative configuration, and as shown in FIG. 8A, a stack 202 can provide
24 selected magnification by utilizing lenslets 204 with differing optical powers: the inner lenslets
25 204a of the stack 202, i.e., those lenslets closer to the optical axis 206, have a lower optical
26 power as compared to the lenslets 204b which are further from the optical axis 206.
27 Additionally, diffractive lenslets can be used to enhance this effect. Note, however, that the
28 main issue addressed with varying optical powers and aperture sizes (including apodization,
29 described herein), is aberration control; while luminance variations (created, for example, by
30 cosine⁴ losses) are addressed by tilting as in FIG. 8A. Accordingly, by changing lenslet power,
31 aperture sizes, apodization, and other parameters discussed herein, optical efficiency can be

1 compensated and corrected as a function of the distance from the optical axis to the edge of the
2 respective arrays.

3 FIG. 9 shows a sequence 210 of stacks 212 arranged along an optical axis 214 so as to
4 provide an erect image 216 of the object 218. As illustrated, the stack 212a has two arrays of
5 refractive lenslets disposed therewith (shown illustratively as two lenslets 220); while stack
6 212b has an array of non-refractive lenslets (shown illustratively as a single lenslet 222). This
7 design provides an internal, inverted image 223 of the object 218 within the first stack 212a so
8 that the final image 216 is erect. Generally, therefore, $2n + 1$ internal images are required to
9 generate an erect image, where n is an integer 0,1,2,3,..... FIG. 9 also shows in internal stop 224
10 arranged within the stack 212a so as to limit the field of view and to restrict the transfer of
11 unwanted radiation (e.g., scattered radiation) to the image 216, thereby boosting MTF. The stop
12 224 can, for example, be micromachined internal to the stack 212a, electro-formed or inserted as
13 a separate element.

14 Similar to FIG. 9, FIG. 9A shows a sequence of stacks 210' arranged along an axis 214'
15 to provide an inverted image 216' of the object 218'. In this configuration, the refractive
16 elements 220' do not generate an internal image; and hence the final image is inverted.
17 Generally, $2n$ internal images within a sequence of stacks will provide a non-erect image, where
18 n is an integer 0,1,2,..... Note that if the stacks do not generate a continuous and erect image, the
19 resulting image 216a'-216c' is jumbled relative to its original appearance since each channel
20 images and inverts a separate FOV, shown illustratively by the dotted sections 218a'-218c' (such
21 as the internal image 223 of FIG. 9).

22 As discussed above, microlenslet surface structures can take on many forms, including:
23 (a) refractive optical elements, (b) diffractive kineforms, (c) high order, high efficiency
24 diffractive steering or focusing lenslets, (d) holograms or holographic lenslets, (e) computer
25 generated holograms, (f) effective index modulating surface arrays, (g) apodizing or other
26 spatial filters, or (h) other features typically generated by lithographic and semiconductor
27 fabrication technology. FIGs. 10-14 illustrate exemplary microlenslets and optical effects
28 created by certain of these lenslet forms.

29 In particular, FIGs. 10A-10C illustrate, respectively, the construction of a holographic
30 lenslet array, a resulting holographic lenslet, and the overall holographic array lenslet operation.
31 In FIG. 10A, a content beam 230 and a reference beam 232 (both typically electromagnetic laser

1 sources such as known to those skilled in the art of holography) interfere within a substrate 234
2 which reacts (such as with emulsion) to form holographic lenslets 236 (shown illustratively as
3 an interference pattern), FIG. 10B. In operation, FIG. 10C, an object 238 which generates a
4 light beam 240 that interacts with the lenslet is "steered" off at the sensitivity angle θ .

5 FIGs. 11A and 11B illustrate, respectively, construction of phase modulation lenslets and
6 the overall operation of phase modulation lenslets. In FIG. 11A, a substrate 242 is modified
7 with phase-changing radiation or deposition 244 so that the phase angle ϕ of the incident
8 electromagnetic field, E , is transformed to E^* by an amount such as ninety degrees, FIG. 11B.

9 FIG. 12A illustrates the manufacture of an index modulating lenslet by ion implantation
10 or exchange. In the illustrated example, the radiation 246 incident on the radiation sensitive
11 substrate 248 is in the form of a Gaussian beam so as to effect either a gradient index lenslet
12 250, FIG. 12B, or a Gaussian-shaped index modulation lenslet 252, FIG. 12C (note that the
13 shape of lenslet 252 is easily modified to another form by changing the shape of the input beam,
14 e.g., to a Bessel irradiance profile). In an alternative index modulating lenslet configuration,
15 FIG. 12D shows a substrate 254 that incorporates a series of nanometer wide cuts 256 that are
16 much smaller than the wavelength of operation. These cuts operate to decrease the density of the
17 substrate and to reduce the effective optical index (i.e., air is about 1.0).

18 Lenslets according to the invention are preferably made with lithographic processes. By
19 way of example, a sequence of photomasks are generated with features that correspond to the
20 desired lenslet dimensions. The substrates are then coated with photoresist. Using a photomask,
21 the resist is then exposed to the sensitizing radiation (typically ultraviolet, electron, or x-ray)
22 followed by curing. The cured and uncured resist are then coated with a metal or other masking
23 material; and the uncured polymer and metal coatings are removed to expose regions of bare
24 substrate. The exposed areas of substrate are then etched using plasma, wet chemical, reactive
25 ions, or other techniques to create a relief pattern. This process is thereafter repeated for
26 successive photomasks to generate a three-dimensional relief structure corresponding to the
27 desired refractive or diffractive lenslet.

28 The making of a negative mold for use in polymer or sol gel molding or replication
29 further illustrates useful lithographic processes in accord with the invention. By way of
30 example, and with reference to FIGs. 13A and 13B, negative lenslet features are first molded
31 into a metal master mold 260; and this mold is used to form a substrate 262 with integral lenslets

1 264 by conventional processes, e.g., injection molding, die pressing, and stamping, known to
2 those skilled in the art. Certain replication techniques, according to the invention, utilize a
3 negative mold as above, and without heating. The mold 260 is coated with a release agent, and
4 followed by the lenslet material 262 in the form of an epoxy, polymer or sol gel. The lenslets
5 features are transferred to a bulk substrate, such as a glass plate, using an adhesive, thermoset or
6 other bonding agent. With reference to FIG. 13B, the flat side 262a, for example, is bonded to
7 such a substrate.

8 FIGs. 14A and 14B illustrate arrays of lenslets 270 formed by diffractive kineforms.
9 FIG. 15A shows a diffractive beam steering lenslet array 272 that redirects a wavefront 274 (of
10 the wavelength corresponding to the micromodulations in the lenslet array 172) at an angle θ (note
11 that such an array can also be a focusing lenslet array). FIG. 15B similarly shows a holographic
12 array of lenslets 276 (or phase or index modulating array) disposed into a substrate 278 to effect
13 beam steering of an incoming wavefront 280. A computer generated hologram lenslet array 282
14 within a substrate 284 provides similar effect to provide focusing of an incident wavefront 286,
15 such as shown in FIG. 15C.

16 FIG. 15D illustrates an array of gradient index (GRIN) lenslets 288 formed by ion
17 implantation, back fill with polymer or gel, or ion exchange as in conventional GRIN elements.
18 FIG. 15E shows an apodization filter 290 that has a selected transmission function (e.g.,
19 Gaussian or anti-Gaussian) and used in conjunction with a kineform lenslet array 292 to effect
20 certain desired transfer characteristics, such as uniformity of illuminance (e.g., cosine-to-the-
21 fourth losses, and modification of Gaussian laser beams). FIG. 15F shows a refractive lenslet
22 array 294 formed in conjunction with an array of stops 296 to effect characteristics such as FOV
23 and luminance uniformity. Within a given array, the stops 296 can include apertures of different
24 diameters so as to (a) be consistent with the lenslet channel diameter or so as to (b) balance
25 illuminance uniformity from the center to the edge of the array. The effect of (b) occurs because
26 lenslets in the center of the array will transmit at greater efficiency as compared to lenslets at the
27 edge of the array unless the lenslet channels at the edge are a different lens configuration or have
28 larger clear apertures. Lenslets can also be formed through lithographic deposition of material
29 for refraction or phase modulation (or retardation), such as shown by the lenslets 298 deposited
30 onto the substrate 300, FIG. 15G.

31 FIGs. 16A-16E illustrate the impact of lenslet FOV on imaging characteristics. The FOV

1 becomes a practical design and fabrication issue due to the relationship between lenslet SAG and
2 curvature given the state-of-the-art fabrication capabilities (that is, the FOV is effectively limited
3 in lenslets with high power - typically small lenslets - since the image at wide field angles is
4 blurred and practically non-existent). If the SAG is less than curvature, then lenslets are,
5 generally, easier to fabricate. In FIG. 16A, an array of lenslets 302 are arranged adjacent to a
6 RGB (red, green, blue) pixelated object 304 such as a color matrix display. In FIG. 16A, the
7 lenslet clear apertures are clearly smaller than the pixelated object dimensions. In FIG. 16B, on
8 the other hand, the lenslet clear apertures 306 are approximately equal to the RGB pixelated
9 dimensions; and in FIG. 16C, the lenslet clear aperture 308 is greater than the pixelated object
10 dimensions.

11 FIG. 17A illustrates an array of lenslets 310 where each of the lenslets has an equal,
12 though non-overlapping FOV 312. Note that in such a case, where little or no FOV overlap
13 occurs, a defective lenslet 310 would result in losing some of the image. However, in the case of
14 FOV overlap 314, such as shown in FIG. 17B, the loss of a single lenslet through defect has a
15 lesser impact on overall image quality since adjacent lenslets 316 transmit some - or all - of the
16 image covered by the defective lenslet.

17 Stacks constructed according to the invention generally include, at least, four lenslet
18 array surfaces formed with at least two substrate elements. Assembly can include discrete air-
19 spaced elements with external mechanical fixturing and/or mechanical spacers placed between
20 the elements and arrays. The mechanical spacers between elements and arrays can be fixed
21 structures or active actuator mechanisms such as MEMS devices with associated electronics and
22 edge or other connector to the external fixturing. Such a stack provides a stable, monolithic
23 structure which easily integrates into a system, device or product. With reference to FIG. 18, a
24 monolithic stack 320 is shown to illustrate the function of fiducial marks, spacers, and interstitial
25 lenslet microalignment features. The stack 320 includes four arrays of refractive lenslets 322
26 disposed with two substrates 324, and two arrays of diffractive lenslets 326 (diffractive kineform
27 type) disposed with two substrates 328, one of which is drilled and pinned with assembly pins
28 330 to a mechanical mount 332. Fiducial marks 334 are used to coalign the arrays of lenslets
29 322, 326 to provide for efficient imaging of the object 336 to the image plane 338. The stack
30 320 additionally has spacers 340 disposed within the stack so as to provide for proper
31 coregistration and spacing between arrays. The spacers 340 can also be drilled and pinned, such

1 as shown as pin 340a, to a substrate. The spacers 340 can be a fixed mechanical structure with
2 or without pins 340a, or an active actuator mechanism such as a MEMS device constructed from
3 a silicon wafer or other suitable substrate that is amenable to processing by microlithographic
4 methods. The actuators of the active spacer 340 provide moveable mechanisms, electronics and
5 connection to the external fixturing to a remote circuit for addressing the actuator mechanisms.
6 Note that coalignment and spacing between arrays can also be made directly from the substrate
7 material, as shown by spacing element 342, or by the mask material 344 arranged at interstitial
8 locations between lenslets 322, such as shown by spacing element 346.

9 FIG. 19 illustrates a Hartman Transform Encoder 350 constructed according to the
10 invention. The encoder 350 divides the optical wavefront (or object space) into discrete parts for
11 individual imaging and analysis. That is, it takes a continuous image 352 and breaks it into a set
12 of discrete pixels 354, each of which is independently evaluated. Accordingly, the SAM 350
13 (including two non-refractive lenslet arrays 350a and two refractive lenslet arrays 350b) of
14 FIG. 19 images a checkerboard object 352 into a corresponding image 354 which can be
15 conveniently coincident with a photodiode array 356 (here shown by a dotted outline, including
16 detector pixels 356a), and associated electronics 358, so as to process individual image signals
17 separately.

18 As discussed earlier, multi-element SAMs of the invention with one or more
19 intermediate image planes facilitate the insertion of passive or active media at a field image or at
20 a collimated space between two lenslets in the stack. Active media located at the field stop
21 provides a convenient forum from which to accomplish optical processing. Consider, for
22 example, FIG. 20, which represents one channel 370 of a stack and which includes an
23 intermediate image 372. The channel 370 further includes a light modifying element 374. By
24 way of example, the element can be a pupil with a selected transmission function, which in
25 linear systems theory provides a canonical processor: the output transform field is the
26 convolution of the corresponding input with the Fourier inverse of the pupil's transfer function.
27 However, the element 374 can also be an electro-optic modulator, a liquid crystal light valve, an
28 active color filter mosaic, a spatial light modulator, a computer generated hologram, an
29 adjustable MEMS actuator at a location between stacks to change via electromechanical means
30 the spacing between stacks in order to modify the optical conjugates of the system, or
31 electromechanical actuators to provide an array of irises or shutters in the path of the optical

1 channels to produce an analog or digital transformation of the optical signal, and even gain
2 media to accommodate a wide variety of applications for optical transform systems, compact
3 optical correlators, optical network and computing systems, switching systems and numerous
4 other optical signal processors. Fixed passive spatial filters, color filters, or encryption filters
5 can also be co-located at the image 372 in the stack assembly to create a wide variety of fixed or
6 passive optical signal processing systems. The inclusion of such devices at the internal image
7 provides optical processing of each of the channels, if desired, in a massively paralleled
8 processor.

9 FIG. 21 shows a scene generation apparatus 380 constructed according to the invention.
10 A computer 382 is used to generate a display pattern on a FPD 384 such as the computer
11 display. A tiled stack 386, shown in a perspective view, thereafter images the display 384 as a
12 large format display 388 suitable for a number of uses (note for clarity of illustration that the
13 computer and display are shown parallel to the optical axis 390 while in fact it would be
14 perpendicular to the axis 390 to enable reimaging). By way of example, the apparatus of FIG. 21
15 is suitable to provide an inexpensive, compact wide FOV display screen 388.

16 FIG. 22 shows a side view of a digital camera constructed according to the invention.
17 Briefly, the camera body 392 and optics 394 are constructed by known methods to generate a
18 35mm film-formatted image plane 396 (shown by a dotted line internal to the body). In accord
19 with the invention, a stack 398 is configured to fit with the body 392 (depending upon the
20 camera body configuration 392, the stack 398 is internal or external to the body and connected
21 by appropriate mechanical fixturing (not shown)) so as to reimage the image plane 396 onto a
22 solid state device 400, e.g., a CCD. In order to achieve this, the stack 398 magnifies or
23 degmagnifies the image 396 selectively so as to fit the pixelated dimensions of the device 400.
24 In this manner, the scene "X" as viewed by the camera 392/394 is conveniently converted to
25 electrical form for display on a device such as a computer 402.

26 FIG. 23 shows a four-element stacked lens array imaging system (SAM) 500 of the
27 invention. The SAM 500 includes a hybrid assembly (i.e., "stack") of lenslet arrays 502, with
28 precise registration among the plurality of individual lenslet optical channels 504 defined by the
29 arrays 502. This allows for optical image transfer from object space 506 to image space 508. The
30 stack 500 assembly of lenslet arrays 502 may perform either magnification or demagnification,
31 depending upon specific applications.

1 More particularly, FIG. 23 illustrates a stack having four elements or substrates 510. In a
2 preferred embodiment, all substrates are silica. Each substrate is illustratively shown with a
3 constant thickness of about 400 microns, though other thicknesses are possible and envisioned.
4 By way of example, the diffractive element substrates 510a may have a thickness of 1.0mm
5 while the refractive element substrates 510b may have a thickness of 300 microns. The stack has
6 a total of two arrays 502a of diffractive lenslets 505a and four arrays 502b refractive lenslets
7 505b, although this number is purely exemplary. For example, in a large screen display, the
8 stack could comprise three diffractive microlens arrays and three refractive microlens arrays.
9 Regardless, each refractive array has integral inter-element stops 512, such as chrome baffles, in
10 open areas (i.e., interstitial regions) between lenslet channels 504 to form entrance and exit
11 pupils, field stop and baffles for stray light rejection and control of crosstalk. The design of the
12 magnifying microlens array stack 500 utilizes arrays of tilted, off-axis optical channels 504 with
13 respect to the central optical axis between the image 508 and object 506.

14 The left surface of the first element 510a1 has a planar surface 511 and is adjacent to the
15 object plane 506. The right surface 514 of the first element 510a1 has diffractive lenslets 505a1
16 that function as aspheric correctors that correct for residual aberration. Both monochromatic
17 aberration and chromatic aberration correction is addressed using diffractive lenslets that
18 provide negative dispersion and which require very little paraxial power to correct for chromatic
19 aberrations.

20 The middle two elements 510b1, 510b2 in the stack 500 of FIG. 23 have refractive
21 lenslets 505b on each array surface 502b. An inverted field image 515 is formed between the
22 second and third elements. The fourth element substrate 510a2 has a left surface 510a' with a
23 diffractive lenslets 505a2 for purposes similar to the first element 510a1. The right surface 516
24 of the fourth element 510a2 is planar and is adjacent to the image plane 508. The four elements
25 510 of the stack may be direct contacted and cemented in place.

26 The stack of FIG. 23 interlaces the images from each optical channel (defined by
27 sequential lenslets in the arrays) to create the final total uniform image 508. If every channel 504
28 were parallel, the demagnified image from one channel 504 would not overlap the image from
29 its neighboring channel. In that case, there would be a demagnified image patch corresponding
30 to each channel surrounded by either a region of no light or a mis-interlaced blur. Thus, the
31 lenslets 505 in the array 502 which are nearest to the image 508 have a higher packing density

1 than the others. This 'off-axis' type of design not only allows the individual channels 504 to
2 have demagnification, but it also allows the array of optical channels to converge towards the
3 final demagnified image. From FIG. 23, it can be seen that the refractive and diffractive lenslet
4 arrays 502 form channels 504 from object to image space that bend inward toward the central
5 optic axis.

6 In a preferred embodiment, the first and last refractive surfaces (left to right) have
7 identical surface figures, while the second and third refractive surfaces (left to right) also have
8 identical surface figures. The lenslet packing configuration is circular apertures on a square
9 Cartesian coordinate array. The clear aperture for the object side is illustratively 10mm by
10 10mm. The overall area for each substrate is illustratively 12.5mm by 12.5mm. Overall, the
11 stack 500 illustratively provides for a 60 by 60 array of optical channels 504. FIG. 23 also
12 illustrates the effect of increasing axial tilt of each optical channel path to converge on the image
13 plane.

14 To simplify fabrication of mask tooling as well as the lenslet arrays, the refractive
15 lenslets (and similarly the diffractive lenslets) within a given array are identical made and
16 uniformly spaced, although this is purely exemplary. By example, the first refractive array
17 502b1 has lenslets 505b with a diameter of 150 μ m and a lens spacing of 161.5 μ m. The second
18 refractive array 510b2 has lenslets 505b with a diameter of 120 μ m and a lenslet spacing of
19 158.5 μ m. The third refractive array 502b3 has lenslets 505b with a diameter of 120 μ m and a
20 lenslet spacing of 157.6 μ m. The fourth refractive array 502b4 has lenslets 505b with a diameter
21 of 100 μ m and a lenslet spacing of 155.8 μ m.

22 In the alternative, the surface of each lenslet array may contain refractive and/or
23 diffractive kineforms, high order, high efficiency diffractive steering or focusing lenslets,
24 holograms, effective index modulating surface arrays, apodizing or other spatial filters, or other
25 features typically generated by lithographic and semiconductor-type fabrication technology. One
26 or more macroscopic planar or refractive lens surfaces may be incorporated in addition to the
27 lenslet array surfaces. Each element in the stack may be of a finite thickness having two
28 surfaces, wherein each surface may have the various characteristics described herein. One
29 surface is typically the input surface for that element, wherein the other surface is typically the
30 output surface for that element.

31 As used herein, the term 'hybrid' sometimes refers to a combination of these different

1 types of optical surfaces (e.g., diffractive, refractive, etc.) for the lenslets in each array.
2 Hybridization provides excellent color aberration or other correction for high efficiency, high
3 modulation transfer function and uniformity over a large aperture optical system.

4 The input and/or output surface of each array provides a clear aperture system with
5 performance at least equivalent to, or greater than, the mechanical aperture of the device. This
6 allows for seamless tiling of the stack optics into an infinitely scaleable, tiled, massive parallel
7 processed array for a very large scale image display or image acquisition over a large field of
8 view. Microelectronics-type fabrication of tiled structures allows for cost-effective
9 manufacturing of large scale assemblies. For example, a single photomask may be used in
10 conventional microlithography and VLSI manufacturing processes to generate the diffractive
11 and refractive lenslet arrays. Massive parallel processing of discrete tile subassemblies allows
12 for cost effective computer control of large scale, seamless tile array systems at very high speeds
13 for real-time video rate (or faster) processing.

14 The system 500 reimages a discrete pixelated object space 506 into a discrete array
15 image space, or reimages a continuous object 506 into a continuous image 508, without dark
16 spaces, gaps or blurred regions between pixels or local image areas at the image plane. This is
17 accomplished by careful image interlacing of adjacent channels 504 or kernels of channels in the
18 stacked array structure.

19 Image interlacing of adjacent microlens channels 504 provides a uniform, high efficiency
20 optical tile system with a total optical path length or working distance which scales with size
21 and f-number of the lenslet channels 504. The system 500 therefore provides for a flat panel
22 optical system with a thickness, weight and mass that is much smaller than a conventional
23 macroscopic lens or mirror optical system.

24 The microlens array element surfaces may consist of a uniform array of lenslets of equal
25 surface figure at regular spacing, or kernels of subarray lenslets of equal surface figure at regular
26 spacing, or uniquely different lenslets at regular, irregular or changing spacing depending upon
27 the location from the mechanical center of the surface.

28 The individual lenslet apertures may be round, square, hexagonal or other shape. Also,
29 the apertures may be equal to or smaller than the lenslet-to-lenslet center spacing, to leave a non-
30 lensed zone between lenslets.

31 Either the lenslets 505, lenslet surfaces and/or inter-lenslet spacing (here shown as items

1 512) may contain hard stops, baffles, masks or opaque zones for control of crosstalk, elimination
2 of stray light, reduction of aberrations, maximization of image contrast, and optimization of
3 modulation transfer function. Intra-element stops 512 or opaque zones may be fabricated by
4 chemical modification of element stops, or opaque zones may be fabricated by chemical
5 modification of element substrate material, trench etching and backfill with opaque materials,
6 thermal or other physical processing. Surface stops may be fabricated using physical deposition,
7 chemical modification, printing or other processes for depositing or locating opaque materials in
8 interstices between lenslets. Inter-element stops 512 or baffles may consist of metal (e.g.,
9 chrome) or other opaque masks which can also provide for accurate spacing and precision
10 location of adjacent lenslets in the array.

11 The design of the stack for stray light control considers four sources of undesirable light.
12 First, it is desirable to block light from the regions between optical channels. Second, it is
13 desirable to eliminate or at least restrict the possibility for light to cross through multiple optical
14 paths and to exit the system at other than designated channels. Third, an antireflection coating is
15 preferably included to eliminate stray light from multiple surface reflections. Fourth, the optical
16 surfaces should have minimal scattering.

17 The third and fourth sources of stray light are addressable upon fabrication of the optics.
18 The first and second sources of stray light require the design of efficient baffles and hard stops
19 between the lenslets. The source of stray light from regions between the optical channels is
20 restricted by coating the surfaces between lenslets with an opaque coating. The second source of
21 stray light is reduced or eliminated by additional baffling or by encapsulating each optical
22 channel in an opaque cylindrical baffle 521.

23 One method by which the system 500 accomplishes magnification or demagnification is
24 by outward or inward tilting of selected lenslet optical channels 504. The system 500 may also
25 utilize lenslet array channels to effect magnification or demagnification by outward or inward
26 tilting of channel optical axes. Magnification or demagnification can be divided equally or
27 unequally among elements 510 of the stack. In a preferred embodiment of the stack of FIG. 23,
28 the amplitude of magnification or demagnification is divided equally about the field image 515
29 between the first and second elements, and the third and fourth elements (left to right).

30 Individual lenslet sizes may be smaller, equal to, or larger than the object or image space
31 pixel dimension. Larger lenslets 505 will encompass fields of view over many pixels in object or

1 image space, or a field which exceeds the aperture of the lenslet with potential overlap among
2 the fields of view of multiple lenslet channels. Lenslets of equal aperture size to field of view in
3 object space 506 may transfer the image of many or just one pixel or field of view equal to the
4 lenslet aperture. Lenslets 505 of smaller aperture size may utilize or interlace the images of
5 many lenslets to image one point in object space to a point in image space.

6 Lenslets which have an aperture size equal to field of view is the least preferred
7 configuration due to the extremely tight tolerance required in fabrication, registration and low
8 defect density needed for good uniformity of image transfer. Designs with the larger lenslet
9 apertures require simpler masks for fabrication with fewer features; but very low defect density
10 can be tolerated unless multiple lenslet channels are used to image a single point in object space.
11 On the other hand, more complicated masks for fabrication are required for lowest packing
12 fraction for optical efficiency, but allow for the greatest tolerance in registration and defect
13 density due to the interlacing of images from many channels to image a point in object space
14 into image space.

15 In one embodiment, approximately five channels transmit light simultaneously from each
16 point in object space to image space. That is, a single point in object space radiates into five
17 adjacent channels in a square pack geometry. Thus, if a lenslet channel has a defect, the
18 information in object space is not lost. Instead, it is transformed by surrounding lenslet channels,
19 but with a fractional loss of intensity. In one embodiment, the resulting field of view for a lenslet
20 in object space is 11.86 degrees or 168 μ m. This imaging of a single point source of light through
21 more than one optical channel increases optical throughput, achieves appropriate image
22 interlacing and maximizes imaging reliability. The illustrated f-number of each lenslet channel
23 504 at design conjugates is f/6.33, while the resulting effective f-number of the stack is
24 approximately f/3.9. Note that a hexagonal close packed arrangement of lenslet arrays could
25 reduce the effective f-number further.

26 The system can provide either inverted or erect-images at the image plane 508 output.
27 Systems with erect images require an odd number (1, 3, 5, or $2n + 1$, where n is an integer
28 number) of field stops or intermediate field image surfaces internal to the stack structure. The
29 simplest configuration has one intermediate image plane 515 where a field stop or field lenslet
30 can be positioned. Systems with inverted image output have zero or an even number of field
31 stops or field image surfaces internal to the stack structure.

1 Systems with internal field images may incorporate field stops in the form of micro-
2 machined, electroformed, molded or other aperture plates for aberration control, improvement of
3 image quality or modulation transfer function.

4 Generally, the minimum requirement contemplated for the imaging system of this
5 embodiment is four array surfaces and two elements. The stack of elements can be assembled as
6 discrete, air-spaced elements with external mechanical fixturing or an internal mechanical
7 spacer. Assembly using an internal mechanical spacer can provide for a stable, monolithic
8 structure for easy integration into a system or product.

9 The element surfaces and/or spacers may include fiducial marks to facilitate micron-level
10 registration and location of components. These fiducial marks can be deposited, or male or
11 female patterns can be etched into surfaces at interstices between microlens elements. The
12 opposing surface of the next element, or the spacer between elements, can also have fiducial
13 marks or mating surface relief patterns to facilitate assembly or co-location of elements and
14 components of the stack assembly. Otherwise, the lenslet apertures can register into one or more
15 mask plates between adjacent elements of the stack to provide for co-location and precise
16 positioning in x-, y- and z-axes of the stack assembly.

17 Monolithic, self-alignment construction of stack assemblies allows for compact, high-
18 performance optical systems with superior structural and environmental integrity, in comparison
19 to conventional optical systems. The system optics can be assembled with buried and cemented
20 surfaces for added reliability and impermeability to contamination or dirt.

21 An intermediate image plane affords the opportunity to design in passive or active media
22 at a field image or collimated space between two arrays in the stack. Optical wavefronts or
23 images can thus be demagnified equally or non-uniformly between input array(s) to the field
24 space and output array(s) to the object space, Active media such as electro-optic modulators,
25 liquid crystal light valves, active color filter mosaics, other spatial light modulators, computer
26 generated holograms, non-linear optical or linear optical, and even gain media, co-located at a
27 field stop accommodate a wide variety of applications for optical transform systems, compact
28 optical correlators, optical network and computing systems, switching systems, and numerous
29 other optical signal processors. Fixed passive spatial filters, color filters, or encryption filters can
30 also be co-located at a field image in the stack assembly to create a wide variety of fixed or
31 passive optical signal processing systems. The compact, monolithic nature of the stack assembly

1 allows for ease of assembly and integration with internal devices plus associated electronics and
2 mechanical fixturing in many applications.

3 The stack components and assemblies of FIG. 23 may be fabricated using a wide variety
4 of materials and methods compatible with volume microelectronics assembly, tooling and
5 equipment. Substrates 510 can be semiconductor, glass, single crystal, polycrystalline, liquid
6 crystal, polymer or other optically transmissive material amenable to processing into microlens
7 arrays. In a preferred embodiment, the hybrid diffractive/refractive optics are fabricated in
8 optical grade polymer using precision replication and molding techniques for minimum
9 thickness, low weight and low cost. Metal or other solid negative masters can be used for mold
10 fabrication of array elements and stacks. Array elements can be cemented to bury surfaces for
11 added reliability. Spacers between elements can be glass, metal, polymer, crystalline or other
12 appropriate structural or optically opaque medium to allow for registration, and for other optical
13 and mechanical properties. Active and passive devices located between elements, particularly at
14 field image planes, may incorporate electronics and mechanics for assembly and fixturing of
15 system products.

16 The system technology can apply to applications across the optical spectrum, from deep
17 ultraviolet to the far infrared. Indeed, many semiconductor materials with ease of processing
18 using microelectronics fabrication technology have excellent infrared transmission properties for
19 novel infrared applications. The compact, flat panel nature of the system of the present invention
20 allows for easy integration with an image plane device such as a focal plane array detector. The
21 system optics can also function as an optical signal processing window that isolates and protects
22 the focal plane array device in a controlled environment atmosphere such as cryogenic or other
23 thermally-controlled environment (e.g., heated, isothermal, non-cryogenically cooled). In
24 addition to environmental protection, use of an active attenuator or filter can afford protection
25 from intense light or unwanted spectral components.

26 The system optics of FIG. 23 thus provide a singular optical assembly in imaging,
27 display or detection applications using a single flat panel display, focal plane array, or other
28 direct display device or detector device. The ability to fabricate system optics with zero edge or
29 clear aperture to the mechanical edge of the output or input surface allows for infinitely
30 scaleable tiling of massive parallel processed arrays for very large flat panel displays or very
31 wide area, high resolution image acquisition systems.

1 Referring now to FIG. 24 (which is a subcomponent to the system embodiment of FIG.
2 25), there illustrated is an embodiment of the optical imaging system 520 of the present
3 invention operable in a magnification mode. The system 520 is used to reimage and magnify the
4 pixelated object display 522 from a miniature FPD to a larger image plane 524. Such miniature
5 electronic displays exploit microelectronics manufacturing technology to produce high
6 resolution, active matrix displays at high yields and low costs. Then, assembly of the hybrid
7 diffractive/refractive microlens array magnifier to a miniature FPD effects a large visible field
8 525 with a high fill factor in a low weight, low profile, high performance package. The result is
9 a viable, scaleable process for economical fabrication of large size passive or active matrix flat
10 panel electronic displays with high efficiency, high resolution and high contrast, but with low
11 profile and low weight for numerous military and commercial applications.

12 FIG. 24 also shows seven lenslet arrays 526 on four substrates 528, and an array of stops
13 configured on a common aperture plate 530. The arrays 526 include either refractive lenslets 532
14 or diffractive lenslets 534.

15 The stack 520 of FIG. 24 is easily integrated into a system such as shown in FIG. 25. As
16 seen in FIG. 25, the output screen 550 of system 549 can be a plurality of tiles 552 that provide
17 the resulting ultra-large flat panel display. Such a display 550 finds common informational
18 display usage in sports stadium and arena scoreboards, high definition television, outdoor
19 advertising, airport runways, entertainment and gaming, virtual environments, virtual
20 conferences, conventions, and countless other areas. The display 550 is a large screen, computer
21 driven, adaptive, active matrix flat panel display with high uniformity of luminance over a wide
22 field angle. The process of tiling a matrix of repetitive stack elements, e.g., a stack 520 of FIG.
23 24, is thus an extremely powerful concept for creating large scale images in a cost effective and
24 reliable manner.

25 The display 550 has utility in areas and markets where well-known and relatively old
26 projection displays will not work or are not appropriate, such as within harsh environments. In
27 extreme environments, a large monolithic FPD 554 often fails, or the image is distorted, due to
28 the extreme temperature range that the FPD 554 is typically exposed to. In contrast, the imaging
29 system 549 isolates and insulates the FPD 554 from the environment. Its structure allows the
30 opportunity to build in a compact heater/cooler to maintain uniformity of FPD performance for
31 all ambient conditions.

1 As another example, conventional avionics displays often suffer from low contrast in
2 direct sunlight. However, the imaging system of the present invention provides a narrower direct
3 field of view to the pilot. The transreflectance surface of the optics reflects and diffuses sunlight
4 for high contrast. The optics of the imaging system also provides for high brightness and
5 contrast at all practical ambient light conditions.

6 With regard to very large electronic message displays like those used in sports stadiums
7 and arenas, these displays suffer from inherent high cost, poor performance, excessive weight
8 and structural problems, enormous power consumption, poor reliability and difficulty and large
9 maintenance expense. In contrast, the ultra-large, high resolution display 550 of the FIG. 25
10 embodiment provides for a seamless, scaleable tile construction. It has all-weather outdoor and
11 indoor direct view capability with a variety of virtual and adaptive screen features.

12 FIG. 25 also shows a computer 556 coupled to FPD boards 558a-d, which serve to drive
13 each of the respective FPDs 554 in the tile.

14 With further reference to FIG. 24, the first element 528a in the stack has a left surface
15 529 that comprises an array of refractive lenslets 532 that receive light from the miniature FPD
16 522. The FPD may be a color array comprising light sources of the three primary colors to
17 achieve a polychromatic display. Color displays are achieved using a kernel format of discrete
18 red, green and blue pixels in a matrix array format in which the colors are repetitively
19 interleaved by alternating rows or columns of a discrete color. The discrete pixel nature of FPDs
20 allows for independent address of individual pixels or multiplexed kernels of pixels. The
21 discrete pixel structure and electronic address capability of FPDs to create images are
22 appropriate for microlens arrays with discrete lenses precisely registered to discrete FPD pixels.
23 Further, the limited wavelength bandwidth of monochrome or polychrome FPD pixels has the
24 advantage of placing limited wavelength dispersion correction constraints on the design of
25 individual lenslets in the arrays. It also allows for blaze angle optimization of diffraction
26 efficiency for optical transfer from the input FPD image plane 522 (i.e., the object plane of the
27 lenslet) to the output image plane of the lenslet array.

28 Furthermore, the microelectronic fabrication of the FPD array structure according to the
29 invention provides for reliable registration and aperture definition of FPD pixels, and provides
30 fiducial registration marks for alignment of individual lenslets and the overall lenslet array to the
31 FPD pixel array.

1 The refractive optics of the left surface of the first element 528a isolate and collimate the
2 light from the FPD 522, and presents the light to the right surface of the second element 528b,
3 which comprises an array of diffractive microlenslets 534. The first element 528a achieves
4 spatial control of the optical emission from the FPD 522 and provides an intermediate image
5 plane (not shown) which can be more effectively transformed by the second element 528b in the
6 stack. The intermediate image plane is needed because oftentimes miniature FPDs have unique
7 optical characteristics that are not necessarily well-suited for efficient optical transfer by a
8 lenslet array.

9 Although not shown, an aperture plate could be placed to the left of the first surface of
10 the first element 528a, possibly located at the Talbot plane of the FPD 522, to define and isolate
11 individual FPD pixels for the left refractive surface of the first element. The two array surfaces
12 of the first element 528a correct for the color bandpass of the associated pixel, and transform the
13 FPD object plane 522 into infinite conjugates for efficient optical processing by the second
14 element 528b in the stack.

15 The second element 528b in the stack is a diffractive microlens 534 array at the right
16 surface, with a planar left surface 527. The lenslet array comprises a plurality of sequential
17 diffractive optical elements 534 that provide for two-dimensional successive incremental angular
18 displacement ("fanout") and, therefore, magnification of the collimated light 529. In a preferred
19 embodiment, the element 528b may achieve four or five times magnification. The fanout grating
20 array is blazed for the appropriate color. The exact incremental angle of the sequential fanout
21 may be between three and fifteen arc-minutes to effect a five times or greater magnification with
22 an aspect ratio of less than one to one.

23 The third element 528c in the stack has a diffractive lenslet array 534 on its left surface,
24 and a refractive microlens array 532 on its right surface. The third element 528c spatially
25 redirects (i.e., re-collimates) the now-expanded light emanating from the second element 528b to
26 near 100% fill factor.

27 The fourth and final element 528d in the stack has a refractive lenslet array 532 on its left
28 surface, and a diffractive microlens array 534 on its right surface. The fourth element 528d
29 serves as the output lens array and may be designed to limit the output field of view, or to effect
30 trans-reflectance optics or other optical transform for contrast enhancement. For example, the
31 fourth element 528d may utilize an additional fanout grating for efficiently modifying the

1 angular field of view for specific angle or wide angle viewing.

2 Each element 528 in the stack may incorporate fiducial registration marks for precise and
3 accurate tolerancing or the overall assembly, as well as registration of the stack to the FPD 522.
4 For example, if the stack is fabricated as a registered stack of air-spaced refractive and
5 diffractive arrays, each stack layer or element is provided with fiducial registration marks to aid
6 in alignment. Simple black nylon or anodized aluminum spacers may be used for precise
7 dimensioning of the air gap of the stack layers. It may also be possible to incorporate etched
8 relief areas and/or thru-holes to aid in registration.

9 In operation, the optical imaging and magnifying system of FIGs. 24 and 25 refracts and
10 diffracts the light from each uniformly spaced pixel in the smaller source array of the FPD. It
11 does so at specifically designed varying angles from the normal to produce a larger tile of
12 discrete sampled array, but with constant magnification, contrast and luminance across the
13 surface.

14 The imaging system of the invention need not be monolithic in construction, but may
15 instead consist of a hybrid stack of optical arrays appropriately registered to each other in the
16 form of a stacked array magnifier (SAM).

17 Further, to control stray light and enhance contrast, a spatial filter or image transfer array
18 may be utilized between the solid state emitter array 522 (i.e., the FPD or LCD) and the
19 magnifier array. Also, it is not necessary that the output display side optics 524 of the system
20 have a 100% fill factor. However, a 100% fill factor to the edge of the output plane provides for
21 seamless tiling of SAM-coupled FPDs to effect scaleable, large format displays limited in size
22 only by the parallel processing computing capability for control and synchronization of the tile
23 elements.

24 It is also not necessary that the stack's pixel format have a square appearance. The
25 output display side 524 of the system is not restricted from including a technical screen or
26 optical array for purposes of enhanced uniformity and field of view.

27 Referring now to FIGs. 26 and 27, there illustrated is the optical imaging stack 570, FIG.
28 26, which is used in a large area, flat panel, X-ray reimager system 580, FIG. 27. In this
29 embodiment, the system 570 is functioning as a demagnifier. Prior art systems suffer from high
30 cost, poor performance, excessive weight and structural problems, along with slow response,
31 high power consumption, poor reliability and difficulty and high cost to maintain.

1 In contrast, the system 580 provides for a seamless, scaleable tile construction with a
2 discrete, low cost CCD readouts 582 integrated by a parallel process computers 584. The system
3 580 of this embodiment is not limited to usage with an X-ray input 586; instead, this
4 embodiment has applications in image intensifiers, very wide field of view and wide azimuth
5 elevation fire control and surveillance systems, diagnostic imaging systems for non-destructive
6 testing and medical applications such as real-time whole body imaging for managed response
7 and trauma treatment.

8 The stack 570 of this embodiment is somewhat similar to that described hereinbefore
9 (FIG. 24) with respect to the ultra-large flat panel display embodiment. The first, second, fourth
10 and fifth arrays 571a, 571b, 571c, 571d are diffractive lenslet arrays which function as kinematic
11 lenslets and low f-number diffractive encoders field lenses to collect and bend light to the first
12 stack refractive lenslet array 571e for focusing onto a CCD array detector assembly 572.

13 X-rays 574 input from a source, such as from medical equipment, pass through a
14 phosphor screen 575 to the first element 573a in the stack (right to left). The right surface of this
15 element 573a is a diffractive array 571a, while the left surface is planar. The function of the first
16 element 573a is to collect photons and collimate the X-ray input.

17 The collimated rays then pass through to the second element 573b in the stack. The right
18 surface of this element 573b is a diffractive lenslet array 571b, while the left surface is a
19 refractive lenslet array 571f. The bent rays emanating from this second element 573b are then
20 directed toward the third element 573c in the stack. This element 573c has a fanout grating and
21 includes a diffractive array 571c. Finally, the collimated rays 575 leaving the third element 573c
22 pass through to the fourth element 573d, which is a refractive/diffractive lens array 571d. The
23 rays are then directed to a CCD 572. In one embodiment, each CCD array camera 572 in image
24 space has square pixels at a pitch of 25 μ m, in at least a 512x512 array measuring 12.7mm
25 square. Thus, a desirable input clear aperture size of the first stack is also at least 12.7 x12.7 mm
26 square.

27 FIG. 27 illustrates the further and related embodiment where a plurality (in this case
28 four) stacks are tiled together to receive the X-ray input 586 from a large phosphor screen 587.
29 Also shown are four CCDs 582, and associated electronics that process the electronic signal
30 output, all at the control of an attached computer 604 connected to the PCI bus 600. The
31 electronics include dedicated control boards 584 (controlled by a common external clock 606

1 and power 608) for each CCD (i.e., a "camera"), along with a frame buffer 588 to capture the
2 data from the control boards 584, an accelerated co-processor 590 to process the video data, and
3 an enhanced display board 592. A hard disk drive 594 may be utilized to store data ultimately
4 displayed on a video display 602.

5 Several CCD detectors with megapixel spatial resolution are commercially available
6 from, e.g., Kodak, Loral Fairchild, Dalsa, Sony, Thomson CSF, EG&G, and Philips. CCD array
7 cameras are also commercially available. Cameras appropriate for this embodiment range in size
8 from 1K by 1K to 2K by 2K nominal pixel resolution. One embodiment, for example, utilizes a
9 4K by 4K pixel resolution tiled array imaging system. This could be accomplished, for example,
10 with four 2K by 2K cameras for a two by two matrix array of stack optics and CCD detectors, or
11 sixteen 1K by 1K cameras for a four by four matrix of stack optics and CCD detectors.

12 The imaging performance of the CCD detectors most likely limits the resolution and
13 performance of a high spatial resolution, array imaging system rather than the stack optics.
14 Although the stack optics will support any CCD pixel size, the demagnification and size of the
15 stack optics should be specific to the CCD chosen. In order for the stack optics to effect the
16 desired integration of the object onto a plurality of detectors without loss of spatial information,
17 the demagnified images of the object should just fill or slightly underfill the CCD active area. If
18 the CCD active area is overfilled by the image from the stack optics, then a final integrated
19 image with poor image interlacing of the object can result. If the demagnified image from the
20 stack optics significantly underfills its corresponding CCD active area, then provision must be
21 made in software to eliminate the imageless perimeter of the CCD active area and appropriately
22 match magnifications of adjacent stack- coupled CCD modules in order to produce a non-
23 distorted image.

24 Standard mega-pixel CCD camera driver, logic and signal processing electronics
25 typically support only a few frames per second readout for a 1K by 1K format or 1K by 2K
26 format due to clock speed, timing and RAM memory capabilities. Larger format CCD cameras
27 use readout circuitry that handles multiple 1K by 2K or 1K by 1K outputs in parallel. Clock
28 rates are typically 20Mhz and readout times of 50ms or more combined with integration times of
29 50ms or more provide less than the desired 30 interlaced frame rate objectives.

30 High speed, DSP-based commercial frame grabbers with extended display boards for
31 video frame rate image representation on PCI or VME bus computers are available. A dedicated

1 Silicon Graphics computer, or 130Mhz Pentium processor with high resolution 2K by 2K
2 monitor may be utilized. Frame grabber boards which can support up to 2K by 2K CCD cameras
3 are also available. Systems integration combines the multiple frame grabber boards and adaptive
4 software to integrate discrete camera module images into memory for display. The display is
5 limited to a subset of the tiled imaging system image, but pan and scroll control allow
6 positioning of the target section of image space at any place in the image file, including at the
7 intersection among two or more stack-coupled CCD detector modules.

8 FIG. 28 and FIG. 29 illustrate optical imaging stacks 610 and 620, respectively, with
9 further and related embodiments, for example, to the four-element stacked lens array imaging
10 system (SAM) 500 of FIG. 23. The stacked lenslet array system 500 in FIG. 23 is designed for
11 optimum imaging performance, f-stop and magnification at a fixed set of object and image
12 conjugates. Furthermore, the spacing of the elements 510 has optimum tolerance of typically +/-
13 25 microns to achieve design performance. In fact, the SAM 500 can perform well at a variety
14 of object and image conjugates with excellent MTF and with only a modest degradation in
15 image resolution over a wide range of magnifications. FIG. 28 and FIG. 29 thus illustrate
16 embodiments that remove fixed variables of the FIG. 23 design.

17 FIG. 28 illustrates a stack 610 with a plurality (in this case four) of lenslet arrays 611a-
18 611d assembled in combination with one or more electro-mechanical stack sections 612. Stack
19 section 612 provides for movable spacing between lenslet arrays 611 internal to the SAM 610
20 for modification of the imaging conjugates and to allow for electronic control adjustment of the
21 focus, f-stop and magnification. The stack section 612 is illustrated further in FIG. 28A-28C
22 (specifically, FIG. 28A and FIG. 28B show different embodiments of the section 612, though
23 both sections 612a, 612b could be used simultaneously - e.g., in a stacked configuration - if
24 desired). Adjustment of the spacing 613 between lenslet arrays 611, combined with a change in
25 object distance and image plane, accommodates a wide range of imaging or optical signal
26 processing conditions. Examples include the digital camera system of FIG. 22 in which the
27 SAM functions as an adjustable camera objective along with an external electro-mechanical
28 stack section 612 between the last stack and the image. Alternatively, a macroscopic means of
29 adjusting the final image conjugate using a motorized screw or other mechanism, for increasing
30 or decreasing the spacing between the stack assembly 610 and the solid state imaging array
31 detector, is employed to effect a miniature adjustable focus and adjustable magnification digital

1 camera.

2 The active, electronically addressable, electro-mechanical stack sections 612a of FIG.
3 28A and 612b of FIG. 28B include a substrate 614a, 614b, respectively, upon which electronic
4 circuitry and electro-mechanical actuators are constructed. The substrates 614 include clear
5 apertures 615 associated with lenslet channels. Electro-mechanical actuators 618a (FIG. 28A)
6 and 618b (FIG. 28B) are placed at the interstices between clear apertures 615 and in contact with
7 adjacent stack elements to facilitate adjustments to the spacing 613.

8 Piezo-electric stack actuators 618a in FIG. 28A are arranged at interstices on one or both
9 sides of the substrate 614a. The piezo-actuators 618a have electrode connections to wiring leads
10 617a1 and 617a2 on substrate circuit board 614a. The substrate 614a circuit has edge
11 connections 615 to external mounting hardware (not shown) for connection to power and
12 electronic control from a remote CPU, computer or analog electronic controller. Electronic
13 impulses delivered to the piezo-actuators 618a cause the actuator to lengthen or contract by
14 electrostriction or the piezoelectric effect, thereby pushing the stacks 611 further apart or
15 drawing them closer to each other.

16 The electro-mechanical actuator section 612b of FIG. 28B illustrates the application of a
17 MEMS device technology to employ micro-miniature motor actuators that adjust the spacing
18 613 between lenslet arrays 611. The MEMS device of FIG. 28B illustrates a pinion gear 618b
19 actuator including of a pancake motor 618b1 driving a gear 618b2 (see FIG. 28C). Rotation of
20 gear 618b2 in contact with lead screw 619 moves the lead screw up or down changing the
21 spacing to the adjacent lenslet arrays. The result is an increase or decrease in the spacing 613
22 between lenslet arrays 611b and 611c, thereby adjusting the location of the field image in the
23 optical system 610.

24 FIGs. 28-28C thus show, in accord with the invention, the use of MEMS actuators
25 between lenslet arrays as a micro-mechanical means of changing optical conjugates for focus or
26 magnification, useful with a digital camera, other detectors, or a display.

27 FIG. 29 illustrates a stack 620 with a plurality (in this case four) of lenslet arrays 621a-d
28 assembled in combination with one or more electro-mechanical, adjustable, electronically
29 activated stack sections 622. FIGs. 29A and 29B show alternative embodiments of the section
30 622, which provide for adjustable apertures in the form of irises or shutters between lenslet
31 arrays internal to the SAM to modify f-stop, light control and/or MTF (or Optical Transform

Function) of the imaging system. Electronically adjustable apertures between lenslet arrays 621 provide an optical system with flexibility to accommodate a wide range of imaging or optical signal processing conditions. Examples of applications for the SAM 620 of FIG. 29 include the optical signal processing system of FIG. 20 and the digital camera system of FIG. 22.

A programmed array of shutters in the internal stack section 622 provides for encoding or decoding optical signals, or for functioning as a compact optical correlator, or performs a similar optical signal transform function in optical signal processing. A programmed array of irises in the digital camera objective lens assembly of FIG. 22, for example, provides for a camera objective in which the f-stop is electronically controlled. Similarly, a programmable array of shutters for the lenslet channels in a digital camera of FIG. 22 can function as, or as a substitute for, the electronic shutter of the focal plane array.

The active, electronically addressable, electro-mechanical stack section 622 of FIG. 29 (shown as the sections 622a of FIG. 9A and 622b of FIG. 29B) includes of a substrate 624a, 624b, respectively, upon which electronic circuitry and electro-mechanical actuators are constructed. The substrate 624 includes clear apertures 624 associated with lenslet channels. MEMS actuators 626 and 636 are placed at the interstices between clear apertures 624. Electromagnet Linear Variable Differential Transformer (LVDT) actuators 626 in FIG. 29A are arranged at interstices on one or both sides of the substrate 624a. The electromagnet MEMS actuators 626 have electrode connections to wiring leads on substrate circuit board 624a. The substrate 624a circuit has edge connection to external mounting hardware for connection to power and electronic control from a remote CPU, computer or analog electronic controller. Electronic signals to the transformer circuit 621 (FIG. 29A-1) of the MEMS LVDT actuator 626 attracts or repels the magnet 627 on armature 628. The armature 628 has a pin 625b connection to shutter or movable iris leaf 629 which is pinned to substrate 624a via pin 625. Motion of the armatures 628a and 628b adjusts the two leafs 629a and 629b of the shutter/iris mechanism 626 to close or open selectively. In closing, therefore, the optical path through 624 of the associated lenslet channel is thereby opened, stopped down, or completely closed, as controlled.

The electro-mechanical actuator element 636 in FIG. 29B illustrates an alternative MEMS device employing micro-miniature motor actuators to stop or shutter the lenslet array aperture 624. The MEMS device of FIG. 29B includes a motor 631 driven pinion gear 637 actuator in a rack and pinion configuration. Rotation of pinions 637a and 637b in contact with

1 racks 638a and 638b open or close leaf mechanisms 639a and 639b to stop down or shutter the
2 aperture 624. FIG. 29B-1 shows a side view of the device 636.

3 FIGs. 29A, 29B and 29B-1 thus show a stack of MEMS actuators controlling an array of
4 shutters or irises between adjacent lenslet arrays. Thus, the optical system f-stop can be actively
5 manipulated or discrete lenslet channel shutters can opened or closed as in a digital camera,
6 other detector, optical signal processor, or a display.

7 In addition to the above embodiments, the invention contemplates usage of the stacked
8 array imaging system in numerous and varied applications besides those described and
9 illustrated herein. The details of these other applications should be apparent to one of ordinary
10 skill in the art in light of the teachings herein. The applications include: large array imaging
11 systems for heads-up displays; low light level image intensifiers; large area, high resolution
12 display systems; solid-state medical imaging systems for high resolution whole body or thorax
13 cavity in real time; low weight, flat panel cockpit displays or imaging systems for avionics or
14 critical missions; spectral applications from deep UV to far infrared; high performance infrared
15 imaging systems; displays for environmental extremes; ultra-large, high resolution, flat panel
16 electronic wall displays; optical encryption systems for security; and other non-destructive
17 imaging besides X-ray.

18 Many other applications for displays and imaging systems are also possible, including
19 active systems where the field stop array at the intermediate image plane is replaced by a spatial
20 light modulator, a phase conjugate medium, or other active or non-linear optical material with
21 index matching properties (e.g., a quantum dot array) for wavelength selective applications. The
22 spatial light modulator may be utilized in an application such as a compact optical correlator.
23 Also, for a compact, low light level aid to the visually-impaired, a microchannel plate having a
24 flat glass phosphor screen input and a flat glass phosphor output may be employed.

25 Further, all of the foregoing has described optics that are totally transmissive. However,
26 a reflective optical device, such as a mirror, may be located at, e.g., an intermediate image plane
27 when it is desired to fold an image of the object back onto itself. In such an application, it may
28 be necessary to utilize a beam splitter in front of the mirror.

29 Those skilled in the art should appreciate that changes can be made within the
30 description above without departing from the scope of the invention. For example, different
31 lenslet array configurations, materials, and applications are easily made and envisioned.

1 The invention thus attains the objects set forth above, among those apparent from
2 preceding description. Since certain changes may be made in the above apparatus and methods
3 without departing from the scope of the invention, it is intended that all matter contained in the
4 above description or shown in the accompanying drawing be interpreted as illustrative and not in
5 a limiting sense.

6 It is also to be understood that the following claims are to cover all generic and specific
7 features of the invention described herein, and all statements of the scope of the invention
8 which, as a matter of language, might be said to fall there between.

9 Having described the invention, what is claimed as new and secured by Letters Patent is:

10

- 1 1. A stacked array magnifier for forming a magnified image of an object, comprising: one
2 or more non-refractive lenslet arrays and one or more refractive lenslet arrays to form a plurality
3 of lenslet channels, each lenslet channel having at least one refractive lenslet and at least one
4 non-refractive lenslet, the lenslet channels between at least two adjacent arrays being sloped
5 relative to an optical axis between the object and the image, the sloped lenslet channels further
6 from the optical axis having larger slopes than the sloped lenslet channels closer to the optical
7 axis, the slopes providing selective magnification between the object and the image.
- 8 2. A magnifier according to claim 1, wherein the lenslet arrays form a stack between a first
9 surface facing the object and a second surface facing the image, the lenslet channels extending
10 further from the optical axis at the first surface and closer to the optical axis at the second
11 surface, thereby providing demagnification of the object at the image.
- 12 3. A magnifier according to claim 2, further comprising a solid state focal plane, the focal
13 plane being substantially perpendicular to the optical axis and arranged at the image to receive
14 electromagnetic radiation thereon from the object.
- 15 4. A magnifier according to claim 1, wherein the lenslet arrays form a stack between a first
16 surface facing the object and a second surface facing the image, the lenslet channels extending
17 further from the optical axis at the second surface and closer to the optical axis at the first
18 surface, thereby providing magnification of the object at the image.
- 19 5. A magnifier according to claim 1, wherein each lenslet channel has a diameter of
20 between about $5\mu\text{m}$ and $1000\mu\text{m}$.
- 21 6. A magnifier according to claim 1, wherein each lenslet channel has a diameter of about
22 $168\mu\text{m}$.
- 23 7. A magnifier according to claim 1, further comprising a macrolens arranged between at
24 least two adjacent arrays, the macrolens being larger than any of the lenslets and providing
25 additional optical power between the object and image.
- 26 8. A magnifier according to claim 1, wherein a plurality of lenslet channels contribute to
27 each point in the image.
- 28 9. A magnifier according to claim 1, wherein the lenslet channels are constructed and
29 arranged to provide a magnification ratio of less than about 8:1 between the object and the
30 image, and further comprising a second stacked array magnifier for providing secondary
31 magnification of the object to a secondary image along the optical axis, the second stacked array

- 1 magnifier having one or more secondary diffractive lenslet arrays and one or more secondary
2 refractive lenslet arrays, the secondary lenslet arrays of the second magnifier forming a plurality
3 of secondary lenslet channels, each secondary lenslet channel having a substantially linear
4 lenslet channel axis with a predefined slope relative to the optical axis, the secondary lenslet
5 channels further from the optical axis having larger slopes than secondary lenslet channels closer
6 to the optical axis, the slopes of the secondary channels providing a magnification ratio of less
7 than about 8:1 between the image and the secondary image, the magnifiers acting in concert to
8 image the object to the secondary image with a magnification ratio that is less than about 64:1.
- 9 10. A magnifier according to claim 1, wherein the lenslet arrays are transmissive to
10 electromagnetic radiation in a wavelength range selected from the group of ultraviolet, visible
11 and infrared radiation.
- 12 11. A magnifier according to claim 10, further comprising a CCD array arranged at the
13 image and substantially perpendicular to the optical axis so as to collect the visible
14 electromagnetic radiation from the object.
- 15 12. A magnifier according to claim 1, wherein the lenslet arrays are transmissive to infrared
16 electromagnetic radiation.
- 17 13. A magnifier according to claim 1, wherein the lenslet arrays are formed of material
18 selected from the group of plastic, semiconductor, and glass.
- 19 14. A magnifier according to claim 1, wherein at least one refractive lenslet array operates
20 to form an intermediate image of the object and within the stacked array, and further comprising
21 a field stop located at the intermediate image to limit the field of view of one or more lenslet
22 channels.
- 23 15. A magnifier according to claim 1, wherein at least one refractive lenslet array operates
24 to form an intermediate image of the object and within the stacked array, and further comprising
25 a lyot stop located at the intermediate image to reduce cross-talk from out-of-field radiation.
- 26 16. A magnifier according to claim 1, wherein the lenslet arrays are transmissive to visible
27 electromagnetic radiation between about 540 and 580nm.
- 28 17. A magnifier according to claim 1, wherein the lenslet arrays are transmissive to visible
29 electromagnetic radiation corresponding to the wavelengths of phosphor and are substantially
30 non-transmissive to radiation outside of the wavelengths.
- 31 18. A magnifier according to claim 1, wherein the non-refractive lenslet array is optimized to

1 achieve diffraction efficiencies within a selected waveband.

2 19. A magnifier according to claim 18, wherein the non-refractive lenslet array
3 comprises a diffractive lenslet array that is optimized with a blaze grating angle.

4 20. A magnifier according to claim 18, wherein the non-refractive lenslet array
5 comprises a diffractive lenslet array that is optimized with a blaze grating angle to provide peak
6 diffraction efficiency at phosphor emission wavelengths.

7 21. A magnifier according to claim 1, wherein each lenslet channel comprises an array of
8 three lenslets at each lenslet array, each of the three lenslets being transmissive to a unique RGB
9 color such that substantially any color can be transmitted along each channel, each of the non-
10 refractive lenslets being optimized for optical efficiency corresponding to the RGB color
11 associated with its channel.

12 22. A magnifier according to claim 1, wherein all lenslets within at least one array are
13 substantially identical.

14 23. A magnifier according to claim 1, wherein the lenslet arrays form a stack between a first
15 surface facing the object and a second surface facing the image, each channel axis extending
16 substantially parallel to the optical axis, thereby providing unit magnification of the object at the
17 image.

18 24. A magnifier according to claim 1, wherein each of the refractive lenslets is substantially
19 identical to other refractive lenslets.

20 25. A magnifier according to claim 1, wherein each of the non-refractive lenslets are
21 diffractive and are substantially identical to other diffractive lenslets.

22 26. A magnifier according to claim 1, wherein each lenslet channel forms an image of part of
23 the object, the lenslets being constructed and arranged so as to produce overlapping images with
24 adjacent lenslets so as to provide a continuous and non-inverted image of the object.

25 27. A magnifier according to claim 1, wherein each lenslet channel forms an image of part of
26 the object, the lenslets being constructed and arranged so as to produce an interlaced image.

27 28. A magnifier according to claim 1, wherein each lenslet channel forms an inverted image
28 of part of the object, the lenslet channels being constructed and arranged so as to produce an
29 array of discrete images of the object.

30 29. A magnifier according to claim 1, wherein each lenslet channel forms an erect image of
31 part of the object, the lenslet channels being constructed and arranged so as to produce an array

1 of discrete images of the object, the array of discrete images being substantially non-overlapping
2 with adjacent images for collection by a solid state sensor.

3 30. A magnifier according to claim 1, wherein each lenslet channel forms an erect image of
4 part of the object, the lenslet channels being constructed and arranged so as to produce an array
5 of discrete images of the object, the array of discrete images being overlapping so as to produce
6 a substantially continuous image of the object.

7 31. A magnifier according to claim 1, further comprising one or more optical coatings on
8 one or more of the lenslet arrays to improve optical transmission through one or more lenslet
9 channels.

10 32. A magnifier according to claim 1, wherein the lenslet arrays form a stack between a
11 first surface facing the object and a second surface facing the image, the lenslet channels being
12 constructed and arranged to form an intermediate image at an intermediate image plane between
13 the first and second surfaces, and further comprising a stop for one or more of (a) reducing stray
14 light, (b) reducing crosstalk, (c) improving modulation transfer function efficiency, and (d)
15 improving contrast transfer function efficiency of the image, the baffling being located at about
16 the intermediate image plane.

17 33. A magnifier according to claim 32, wherein the stop comprises an active micro-
18 mechanical actuator with an electronically addressable and adjustable aperture.

19 34. A magnifier according to claim 32, wherein the stop is within a blur distance from the
20 intermediate image plane, the blur defining a distance within which the image is not degraded by
21 a wavefront error greater than about $\frac{1}{4} \lambda$.

22 35. A magnifier according to claim 1, wherein the lenslet arrays form a stack between a first
23 surface facing the object and a second surface facing the image, and further comprising masking
24 material arranged within the stack to reduce stray light transmission from the object to the
25 image.

26 36. A magnifier according to claim 35, wherein the masking material is formed on a surface
27 of at least one of the lenslet arrays.

28 37. A magnifier according to claim 36, wherein the masking material is arranged between at
29 least two refractive lenslets.

30 38. A magnifier according to claim 36, wherein the masking material is arranged between at
31 least two non-refractive lenslets.

1 39. A magnifier according to claim 35, wherein the masking material reduces stray light
2 cross-talk to less than about 10% of all of the electromagnetic radiation transmitted from the
3 object and to the image.

4 40. A magnifier according to claim 1, wherein the lenslet arrays form a stack between a first
5 surface facing the object and a second surface facing the image, wherein each of the lenslets of
6 the first surface have a field of view, the fields of view of the first surface lenslets being
7 substantially edge-to-edge with the other fields of view, at the object, so that a substantially
8 continuous image is achieved.

9 41. A magnifier according to claim 1, wherein the lenslet arrays form a stack between a first
10 surface facing the object and a second surface facing the image, wherein each of the lenslets of
11 the first surface have a field of view, the fields of view of the first surface lenslets being
12 overlapping with the other fields of view so that a substantially continuous image is achieved.

13 42. A magnifier according to claim 1, wherein the lenslet arrays form a stack between a first
14 surface facing the object and a second surface facing the image, wherein at least one of the
15 arrays forms an intermediate image of the object between the first and second surfaces, and
16 further comprising a field stop to limit the field of view of at least one lenslet channel.

17 43. A magnifier according to claim 1, wherein each of the lenslet channels is constructed and
18 arranged so as have a lenslet f-number such that the overall f-number of the magnifier is less
19 than the lenslet f-number.

20 44. A magnifier according to claim 22, wherein each of the lenslet channels is constructed
21 and arranged so as have an f-number of $f/1$ or greater such that the overall f-number of the
22 magnifier is less than about $f/1$.

23 45. A magnifier according to claim 1, wherein each of the lenslet channels has an active,
24 electronically addressable, adjustable f-stop, the f-stop comprising one of an actuator assembly,
25 a tunable iris, and a shutter mechanism.

26 46. A magnifier according to claim 1, wherein each of the non-refractive lenslets is a
27 diffractive lenslet include means for creating diffraction orders of electromagnetic radiation
28 transmitted between the object and the image, the orders being sufficient to provide greater than
29 approximately 90% efficiency.

30 47. A magnifier according to claim 1, further comprising means for improving resolution of
31 the object such that the image has a modulation transfer function of greater than about 10% at

- 1 image frequencies greater than about 500 lp/mm.
- 2 48. A magnifier according to claim 1, further comprising means for improving resolution of
3 the object such that the image has a modulation transfer function of greater than about 10% at
4 image frequencies greater than about 500 lp/mm.
- 5 49. A magnifier according to claim 48, wherein the means for improving resolution includes
6 at least one refractive optical surface having an aspheric shape.
- 7 50. A magnifier according to claim 1, further comprising means for reducing distortion
8 within the image to less than about 2%.
- 9 51. A magnifier according to claim 1, wherein the means for reducing distortion comprises
10 edge lenslets having more or less power than other lenslets within the same array, the edge
11 lenslets being adjacent to one or more edges of the magnifier to compensate for pincushion,
12 barrel or petzval distortion.
- 13 52. A magnifier according to claim 1, wherein the non-refractive lenslet array comprises one
14 or more of the following: a diffractive lenslet array, a holographic lenslet array, a phase
15 modulating array and a index modulating surface array.
- 16 53. A magnifier according to claim 1, further comprising one or more of a spatial filter and
17 an apodizing filter.
- 18 54. A magnifier according to claim 53, wherein the spatial filter comprises an array of stops
19 with different diameters.
- 20 55. A magnifier according to claim 1, comprising one or more active, electronically
21 addressable, adjustable MEMS devices for changing the spacing between lenslets in order to
22 change focal properties and magnification.
- 23 56. A magnifier according to claim 1, comprising one or more active, electronically
24 addressable micromechanical iris/shutter for one of changing the f-stop of lenslets and of
25 activating/deactivating select lenslet channels.
- 26 57. A magnifier according to claim 1, further comprising at least one lenslet array of planar
27 refractive surfaces.
- 28 58. A magnifier according to claim 1, wherein the refractive and non-refractive lenslet arrays
29 include, in combination, means for affecting one or more of the following image characteristics:
30 modulation transfer function, aberration, throughput efficiency, color correction, and uniformity.
- 31 59. A magnifier according to claim 1, wherein the refractive and non-refractive lenslet arrays

- 1 include, in combination, means for creating image distortion selectively.
- 2 60. A magnifier according to claim 1, wherein at least one of the arrays comprises a plurality
3 of tiled arrays, each of the tile arrays acting in concert to optically function as a single array.
- 4 61. A magnifier according to claim 60, wherein each of the tile arrays has a clear aperture
5 extending substantially over 100% of the tile array such that the plurality of tile arrays
6 seamlessly combine as a single array without substantially affecting the image.
- 7 62. In a method of manufacturing a microlenslet array of the type having a plurality of
8 lenslets formed within a optical substrate having a first planar surface, a second planar surface,
9 and a normal vector that is substantially perpendicular to each surface, the improvement
10 comprising the steps of forming a first lenslet array within the first surface, forming a second
11 lenslet array within the second surface, forming a plurality of lenslet channels between the
12 lenslet arrays wherein each channel includes one lenslet from each of the arrays, the lenslet
13 channels between at least two adjacent arrays having a channel axis vector relative to the normal
14 vector such that the cross product between the channel axis vector and the optical axis vector is
15 greater for lenslet channels further away from a line extending along a center of the substrate
16 and parallel to the normal vector.
- 17 63. In a method according to claim 62, a further improvement wherein the step of forming a
18 plurality of lenslet comprises the step of forming lenslets selected from the group of diffractive
19 lenslets, holographic lenslets, phase modulating lenslets, index modulating lenslets, and
20 refractive lenslets.
- 21 64. A method of manufacturing a microlens stack having an optical magnification for
22 producing an image of an object along an optical axis, comprising the steps of: combining at
23 least two refractive lenslet arrays with at least one diffractive lenslet array to form a lenslet array
24 stack with a plurality of lenslet channels, each of the channels having a sloped axis between at
25 least two of the arrays, and arranging the channels such that the cross product between the
26 sloped axis and the optical axis is greater for lenslet channels further from the optical axis as
27 compared to lenslet channels closer to the optical axis, thereby achieving the magnification
28 selectively.
- 29 65. A method according to claim 64, further comprising the step of arranging the channels
30 such that at least two channels contribute to the image of each point of the object.
- 31 66. A method according to claim 64, further comprising the step of arranging at least one

1 array so as to produce an intermediate image of the object and between other arrays, and further
2 comprising a field stop located at the intermediate image so as to reduce the field of view of at
3 least one channel.

4 67. A method according to claim 64, further comprising the step of arranging, between the
5 arrays, one or more active, electronically addressable, adjustable actuator mechanisms fabricated
6 into a substrate by microlithographic techniques for one of (a) changing channel f-stops, (b)
7 shuttering lenslet channels, or (c) modulating spacing between arrays.

8 68. A tiled array imager for generating an image of an object along an optical axis between
9 the object and the image: at least two tiled arrays forming a lenslet array stack arranged
10 substantially perpendicular to the optical axis, each of the tiled arrays formed of a plurality of
11 lenslet arrays including one or more non-refractive lenslet arrays and one or more refractive
12 lenslet arrays, each lenslet array within a tiled array acting substantially in concert as a single
13 lenslet array, the tiled arrays forming a plurality of lenslet channels, each lenslet channel
14 between at least two arrays having a channel axis with a predefined slope relative to the optical
15 axis, the lenslet channels further from the optical axis having larger slopes than lenslet channels
16 closer to the optical axis, the slopes providing demagnification between the object and the
17 image.

18 69. A tiled imager according to claim 68, wherein the non-refractive lenslet arrays comprise
19 one or more of diffractive lenslet arrays, holographic lenslet arrays, phase modulating arrays,
20 and index modulating surface arrays.

21 70. A tiled imager according to claim 68, further comprising means for forming an
22 intermediate image between at least two arrays, and further comprising a field stop for limiting
23 the field of view of at least one channel.

24 71. Scene generating apparatus, comprising:
25 a computer for generating signals representative of an selected pattern;
26 flat panel display means responsive to the signals to display the pattern, the display means
27 having a display center and a normal vector perpendicular to a face of the display means;
28 a plurality of lenslet arrays formed into a stack having a plurality of lenslet channels, the
29 channels between at least two arrays having a sloped channel axis relative to the surface normal
30 vector, the lenslet arrays being constructed and arranged to generate an image of the pattern on
31 the display means, the cross product of the sloped channel axis and the surface normal vector

1 being larger for channels further from the center as compared to channels closer to the center
2 wherein selective magnification of the image is achieved.

3 72. Scene generating apparatus according to claim 71, wherein each of the arrays comprises
4 a plurality of tiled lenslet arrays that act substantially in concert as a single optical lenslet array.

5 73. Scene generating apparatus according to claim 71, wherein the flat panel display
6 comprises a liquid crystal display.

7 74. Scene generating apparatus according to claim 71, wherein each of the arrays comprises
8 a plurality of tiled lenslet arrays formed into an x,y array that act substantially in concert as a
9 single optical lenslet array.

10 75. A method of manufacturing a scaleable large screen display from an electronic display of
11 the type having a center and a substantially planar surface with a surface normal perpendicular
12 to the surface, the display of the type selected from the group consisting essentially of an LCD
13 display, a cathode ray tube, and one or more laser diodes, comprising:

14 selecting a desired magnification of the display;

15 forming a tiled array of stacked lenslet arrays, the tiled array corresponding to magnification of
16 the display, the stacked arrays within each tiled array operating in concert with every other
17 stacked array within the tiled array so as to operate substantially as a single lenslet array, each
18 stacked lenslet array being formed through the following steps:

19 forming at least one array of refractive lenslets into a first optical substrate and at least one other
20 array of non-refractive lenslets into a second optical substrate, the non-refractive lenslets being
21 selected from the group consisting essentially of diffractive lenslets, holographic lenslets, phase
22 modulating lenslets, and index modulating lenslets, arranging the arrays into a stack having a
23 plurality of lenslet channels, each of the channels having at least one refractive lenslet and one
24 non-refractive lenslet, and wherein the step of arranging the arrays includes the step of creating a
25 sloped channel axis between at least two arrays and relative to the surface normal,
26 arranging the tiled arrays to operate in concert such that the sloped channel axis is larger for
27 channels further from the center as compared to channels closer to the center wherein the desired
28 magnification of the display is achieved.

29 76. A digital camera, comprising:

30 a film-formatted camera body and camera lens which generate an image of a scene at an
31 image plane within the camera body and in a format corresponding to 35mm film.

1 one or more non-refractive lenslet arrays and one or more refractive lenslet arrays
2 formed into a stack with a first outer surface and a second outer surface, the stack being
3 constructed and arranged to fit within the camera body such that the first surface is at the image
4 plane, the lenslet arrays forming a plurality of lenslet channels which act in concert to form a
5 secondary image that is sized to a solid state focal plane array; and

6 a solid state focal plane array arranged at the secondary image.

7 77. A digital camera, comprising:

8 a solid state imaging device of the type that includes an array of detector pixels
9 responsive to electromagnetic radiation within a range of wavelengths;

10 a window for protecting the device and for imaging the radiation onto the device, the
11 window having one or more non-refractive lenslet arrays and one or more refractive lenslet
12 arrays formed into a stack, the stack being constructed and arranged over the device and forming
13 a plurality of lenslet channels which act in concert to form an image that is sized to the device.

14 78. A camera according to claim 77 wherein the lenslet channels are sloped between at least
15 two arrays and relative to a surface normal of the device so as to increase a field of regard of the
16 window.

17 79. A four-array reimaging system for generating an image of an object along an optical
18 axis, comprising: a pair of refractive lenslet arrays sandwiched between a pair of diffractive
19 lenslet arrays, the arrays being substantially perpendicular to the optical axis and forming an
20 array of co-registered lenslet channels, each of the lenslet channels having a plurality of
21 refractive lenslets and a plurality of diffractive lenslets.

22 80. A system according to claim 79, further comprising a plurality of inter-lenslet channel
23 stops, each stop being constructed and arranged to form baffling between adjacent lenslet
24 channels.

25 81. A system according to claim 79, further comprising a plurality of inter-lenslet channel
26 stops, each stop being constructed and arranged to form one of an aperture stop or field stop
27 along a lenslet channel.

28 82. A system according to claim 79, further comprising an active actuator mechanism
29 arranged between lenslet arrays as a spacer for one or more of (a) changing camera f-stop, (b)
30 shuttering, and (b) modulating spacing between arrays to change camera focus.

31 83. A system according to claim 79, wherein each of the arrays comprise a tiled array of sub-

- 1 arrays, the sub-arrays acting in concert as a single lenslet array.
- 2 84. A system according to claim 79, wherein each of the arrays is formed into a separate
3 optical substrate such that the system contains eight surfaces.
- 4 85. A system according to claim 79, wherein at least one of the arrays forms an
5 intermediate image between two arrays, and further comprising a field stop arranged at the
6 intermediate image to limit the field of view of one or more channels.
- 7 86. A system according to claim 79, further comprising one or more optical baffles located
8 on one or more arrays, or between two arrays, to block stray radiation at the image.
- 9 87. A system according to claim 79, wherein at least one of the arrays forms an
10 intermediate image within a substrate of one array, and further comprising means arranged at the
11 intermediate image to limit the field of view of one or more channels.
- 12 88. Hybrid lenslet imaging apparatus, comprising an array of lenslet channels, each channel
13 having at least one refractive optical element and at least one non-refractive optical element, the
14 array forming an image of an object plane wherein a plurality of lenslet channels contribute to
15 each point in the object plane.
- 16 89. Apparatus according to claim 88, wherein the non-refractive optical elements comprise
17 one or more diffractive lenslets, holographic lenslets, phase modulating lenslets, and index
18 modulating lenslets.
- 19 90. Discrete pixel array image relay apparatus, comprising at least one refractive lenslet
20 array and one non-refractive lenslet array, the arrays being constructed and arranged between
21 first and second surfaces to form a plurality of lenslet channels which, in combination, generate
22 an image of a discrete pixel array.
- 23 91. Apparatus according to claim 90, wherein the discrete pixel array comprises a discrete
24 light source selected from the group of CCDs, phosphor screens, flat panel displays, LCDs, and
25 one or more laser diodes.
- 26 92. Apparatus according to claim 90, further comprising a phosphor surface arranged
27 substantially in contact and adjacent to the first surface, and further comprising a solid state
28 device arranged substantially in contact and adjacent to the second surface, thereby providing
29 reimaging of the phosphor between the first and second surfaces.
- 30 93. A compact optical correlator for imaging an object to a solid state detector, comprising:
31 a first stack and a second stack arranged substantially perpendicular to an axis formed between

1 the object and the detector, each stack having one or more non-refractive lenslet arrays and one
2 or more refractive lenslet arrays, the lenslet arrays forming a plurality of lenslet channels
3 wherein each channel includes one lenslet from each of the other arrays, the first stack
4 generating a Fourier image between the first and second stacks at a filtering plane, the second
5 stack generating an image of the Fourier image such that the object is reimaged onto the
6 detector; and
7 an optical filter arranged at the filtering plane for selectively filtering electromagnetic energy so
8 as to achieve selected optical processing.

9 94. A method of manufacturing a stack of lenslet arrays for imaging an object to an image,
10 comprising the steps of: forming one or more non-refractive lenslet arrays and one or more
11 refractive lenslet arrays, forming a plurality of lenslet channels and arranging the channels such
12 that each lenslet channel has at least one refractive lenslet and at least one non-refractive lenslet,
13 and arranging the lenslets within a channel to achieve a selected magnification between the
14 object and image.

15 95. A method according to claim 94, further comprising the step of forming at least one of
16 the arrays through one of (a) molding of an optical grade polymer and (b) coextrusion of an
17 optical polymer, with an opaque polymer.

18 96. A method according to claim 94, further comprising the step of fabricating the lenslets
19 from a negative relief to generate surface features, plus fiducial marks and mechanical assembly
20 features, the negative relief being fabricated into a metal, ceramic or high temperature composite
21 master.

22 97. A method according to claim 96, further comprising the step of transferring a positive
23 master in glass, semiconductor or crystal material to a ceramic or elastomer template to form a
24 negative mold master.

25 98. A method according to claim 94, further comprising the step of forming the arrays from
26 different optical materials so as to correct for optical color aberrations.

27 99. A method according to claim 94, further comprising the step of manufactured at least
28 two of the arrays through replication, including the steps of fabricating a mold from a negative
29 relief of the refractive and non-refractive lenslets, and of fabricating fiducial and mechanical
30 assembly features within the stack.

31 100. A method according to claim 99, further comprising the step of fabricating the relief

- 1 from a metal, ceramic or high temperature composite master which is produced by
2 micromachining or by direct forming into a master mold material.
- 3 101. A method according to claim 100, further comprising the steps of coating the master with
4 a release agent followed by one of (a) an epoxy, (b) a polymer, (c) an optical quality organic,
5 and (d) a sol gel material to produce a thin sheet of material with lenslet array features, fiducial
6 marks, and mechanical assembly features.
- 7 102. A method according to claim 94, further comprising the step of fabricating opaque
8 interstitial areas to provide for stops and to eliminate or reduce optical crosstalk among nearby
9 lenslet channels.
- 10 103. A method according to claim 94, further comprising the step of fabricating the lenslet
11 arrays with fiducial features to facilitate alignment and registration of lenslet array channels in
12 cartesian x-y and rotational coordinates.
- 13 104. A method according to claim 103, further comprising the step of locating the fiducial
14 features at one or more of (a) outside of the lenslet clear aperture and (b) interstitial to the lenslet
15 array features.
- 16 105. A method according to claim 103, further comprising the step of arranging the fiducial
17 features as one or more of (a) a frame around the lenslet array mask, or parts of the lenslet array
18 mask, (b) within interstitial regions to the lenslet array channels, (c) horizontal or vertical lines,
19 sequences of lines, crossed lines, circles, squares, hexagons, other geometrics or combinations of
20 geometric shapes.
- 21 106. A method according to claim 103, further comprising the step of arranging fiducial
22 marks such that a Moire pattern is generated upon assembly of the arrays, thereby indicating
23 proper registration.
- 24 107. A method according to claim 103, further comprising the step of making the fiducial
25 marks and assembly features out of material used in the masking of the interstitial and
26 surrounding regions of the lenslets.
- 27 108. A method according to claim 103, further comprising the step of making the fiducial
28 marks and assembly features as etched features within the array substrate.
- 29 109. A method according to claim 103, further comprising the step of making the fiducial
30 marks and assembly features out of mechanical spacers for placement within the stack.
- 31 110. A method according to claim 103, further comprising the step of forming the fiducial

- 1 marks out of one of a material that transforms from a solid to a liquid when subjected to heat or
2 other activation such that a surface tension is created to promote alignment of the stack.
3 111. A method according to claim 110, further comprising the step of retransforming the
4 material of the fiducial and assembly features back to a solid, thereby bonding the stack together
5 into a monolithic structure.
6 112. A method according to claim 110, further comprising the step of assembling the stack
7 with the material at one or more of (a) edges of the stack or (b) internal locations of the stack.
8 113. A method according to claim 103, further comprising the step of immersing the arrays
9 with adhesive for monolithic bonding of the stack.
10 114. A method according to claim 103, further comprising the step of adding thru-holes
11 within the stack so as to provide for the insertion of micromechanical pins which assist stack
12 assembly and which mechanically tie the stack into a monolithic structure.
13

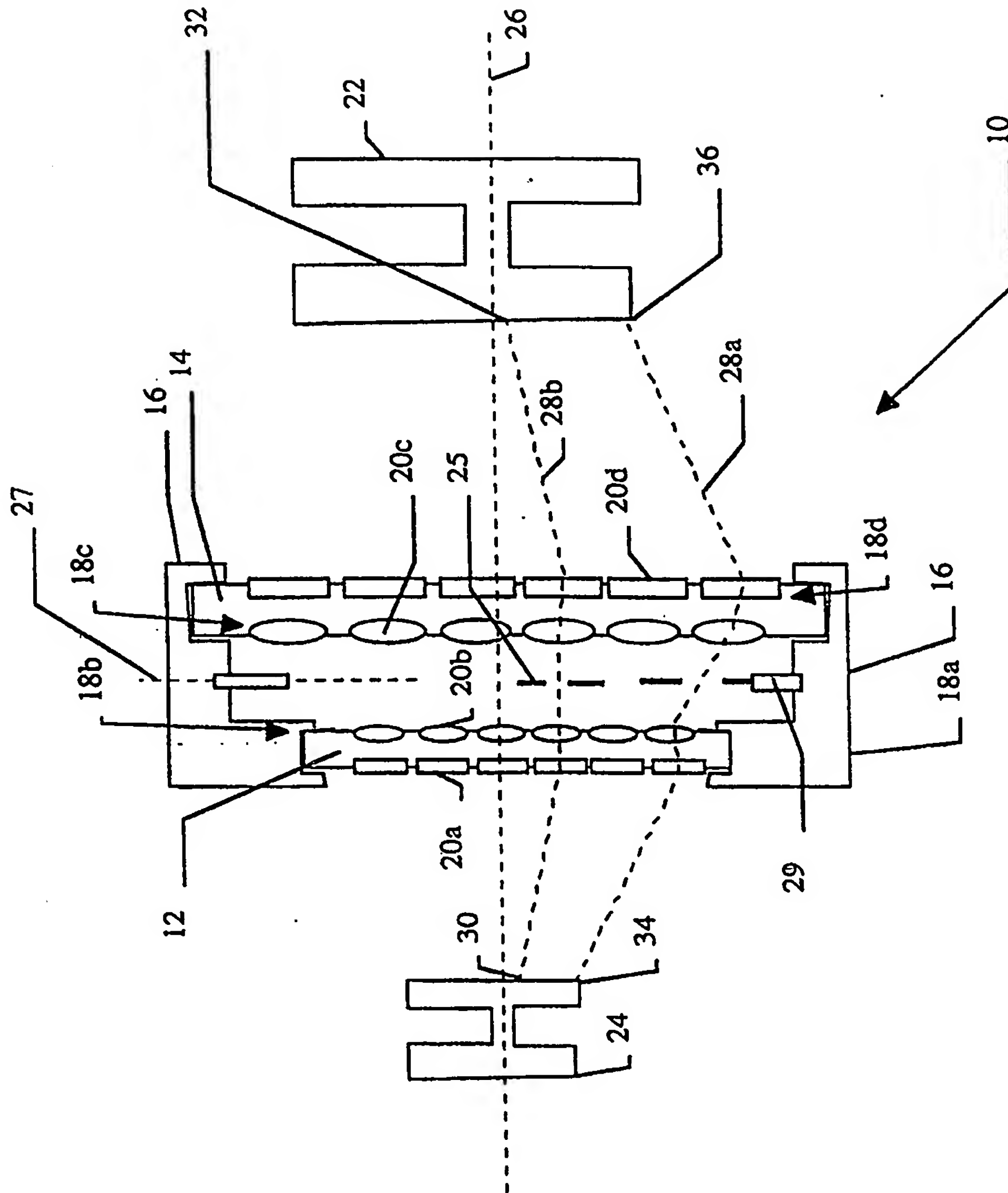


Figure 1

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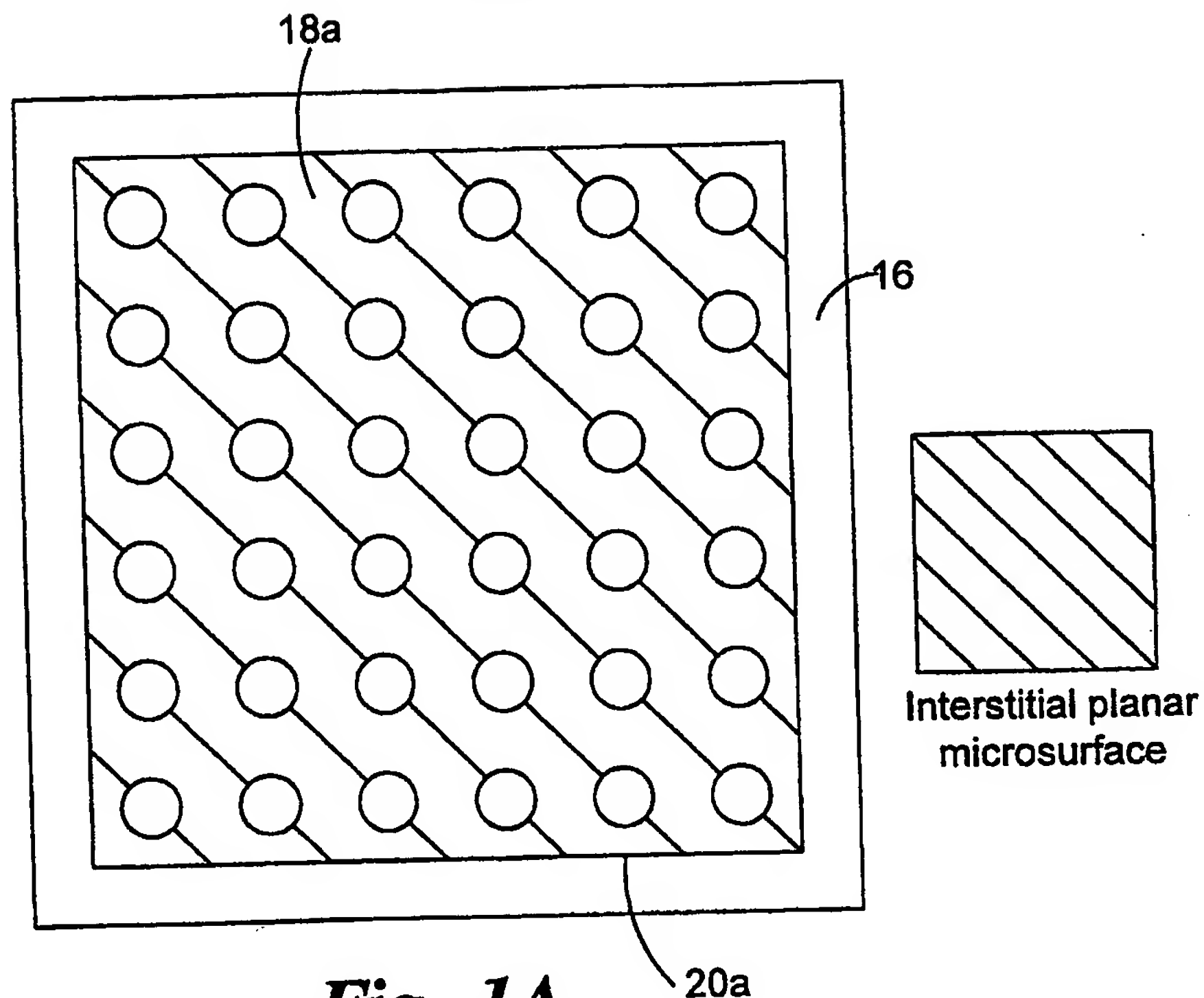


Fig. 1A

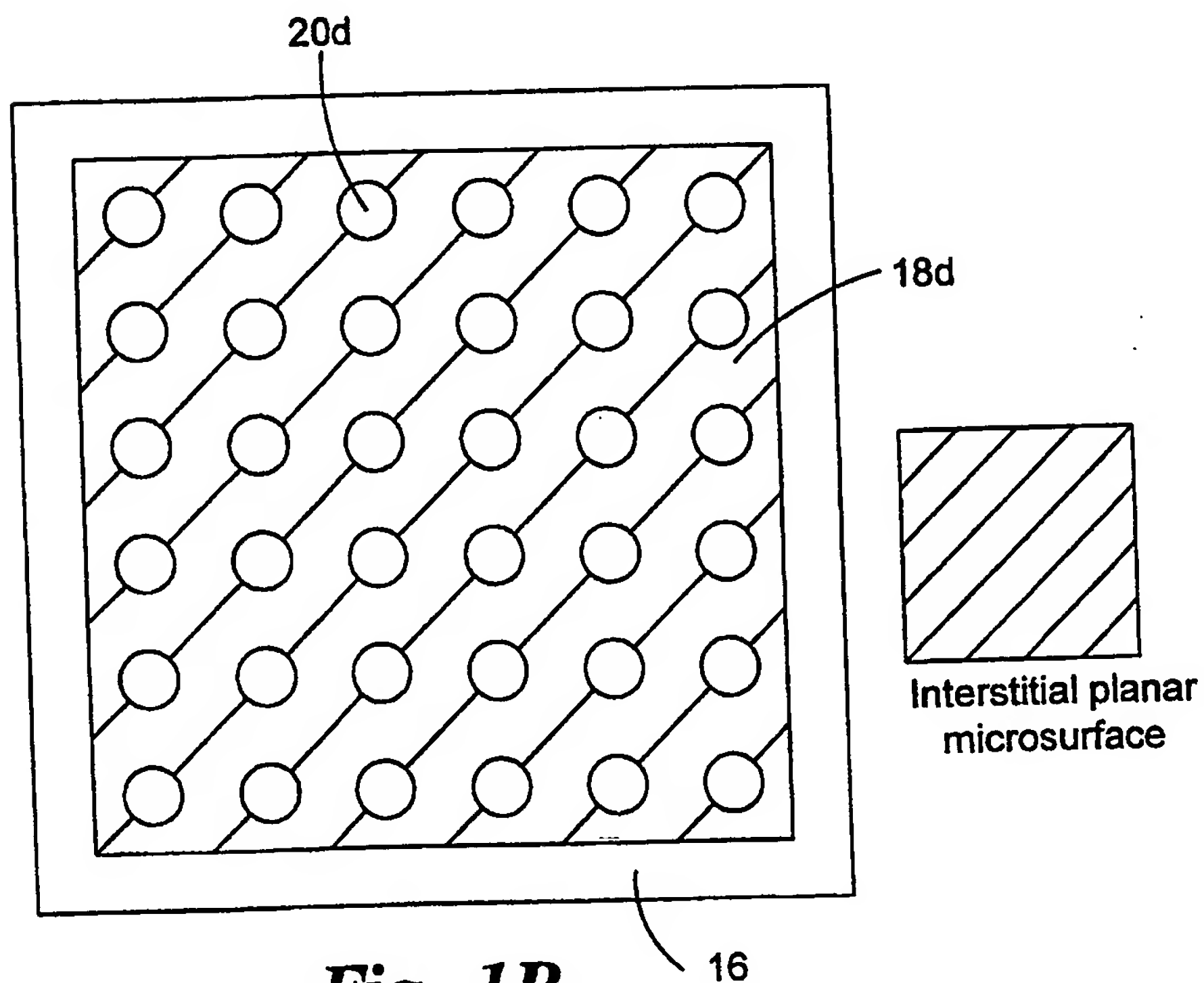


Fig. 1B

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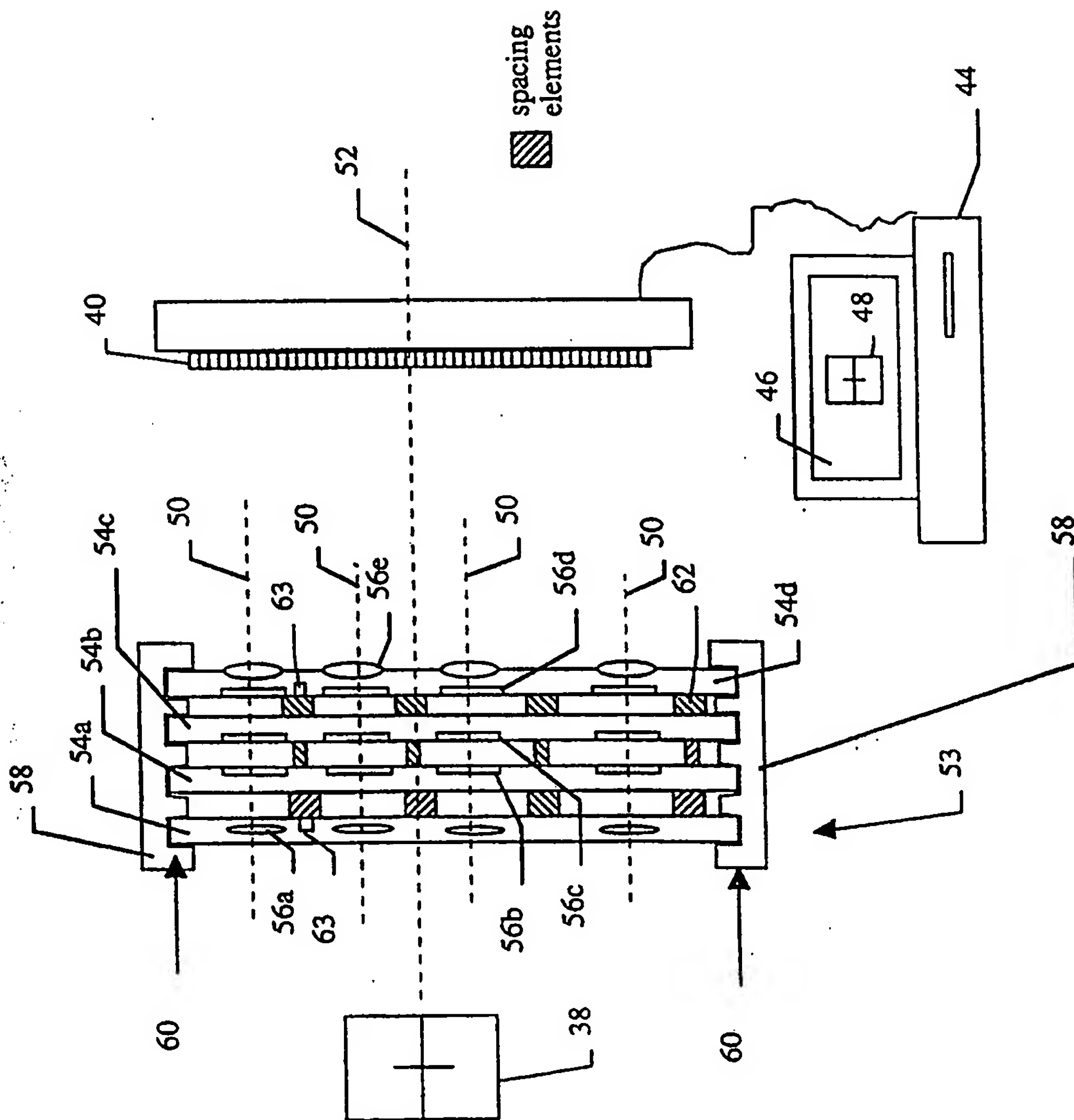
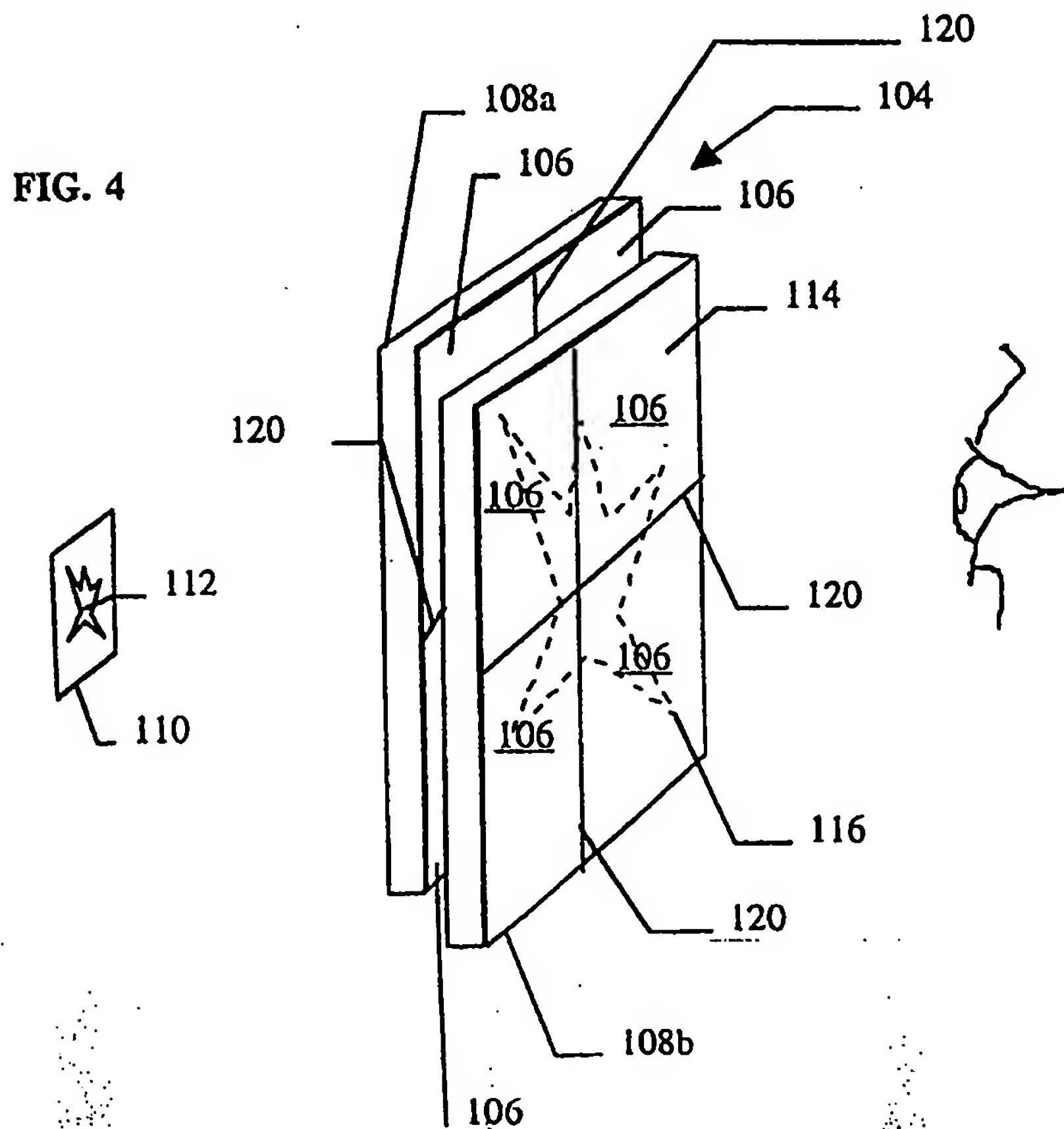
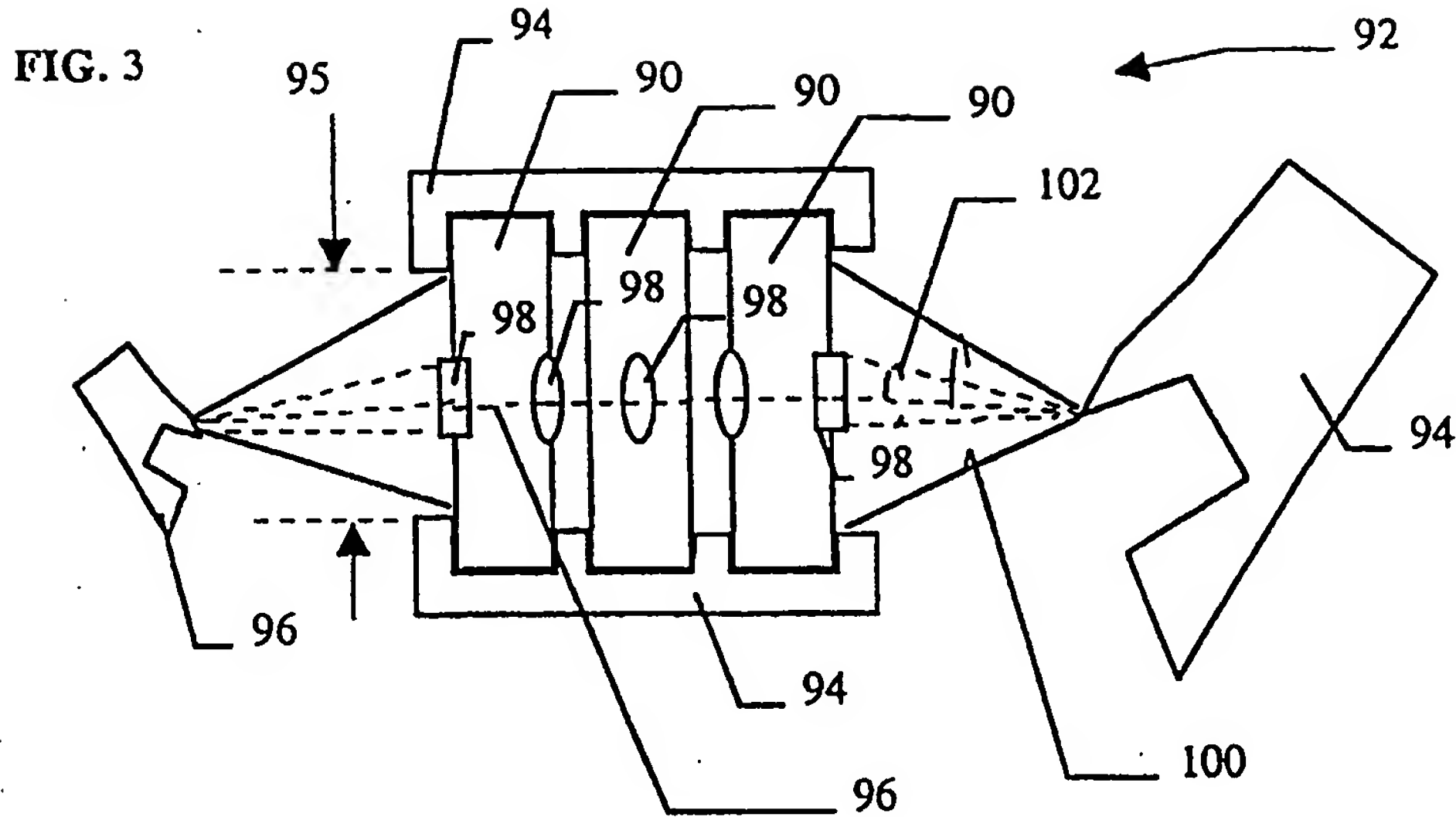


Figure 2

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FIG. 5

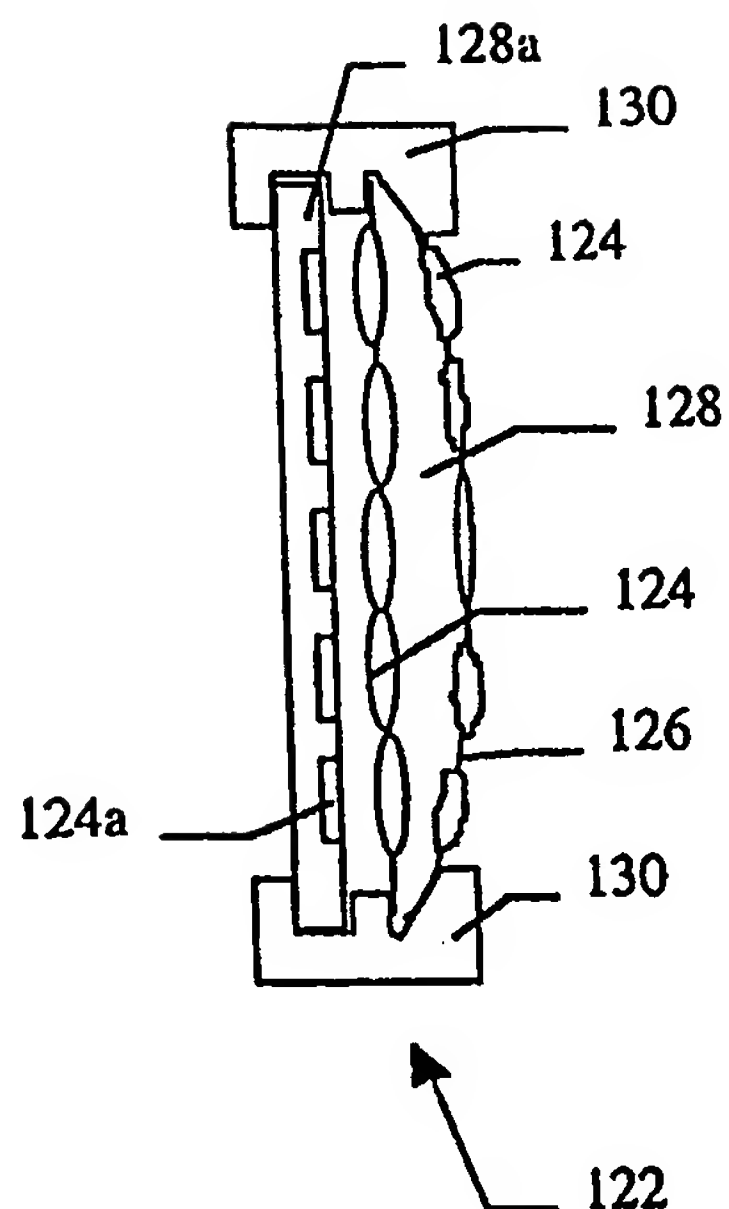


FIG. 6A

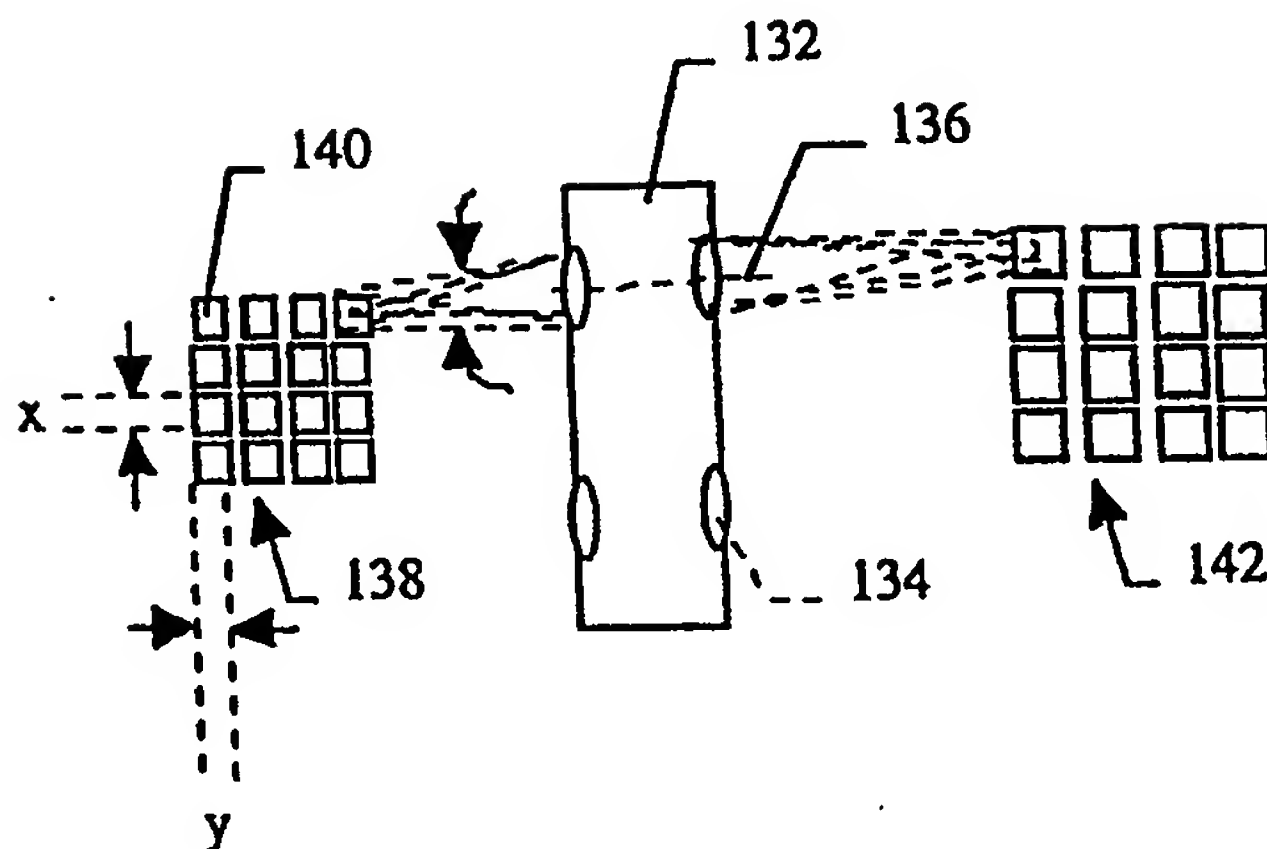
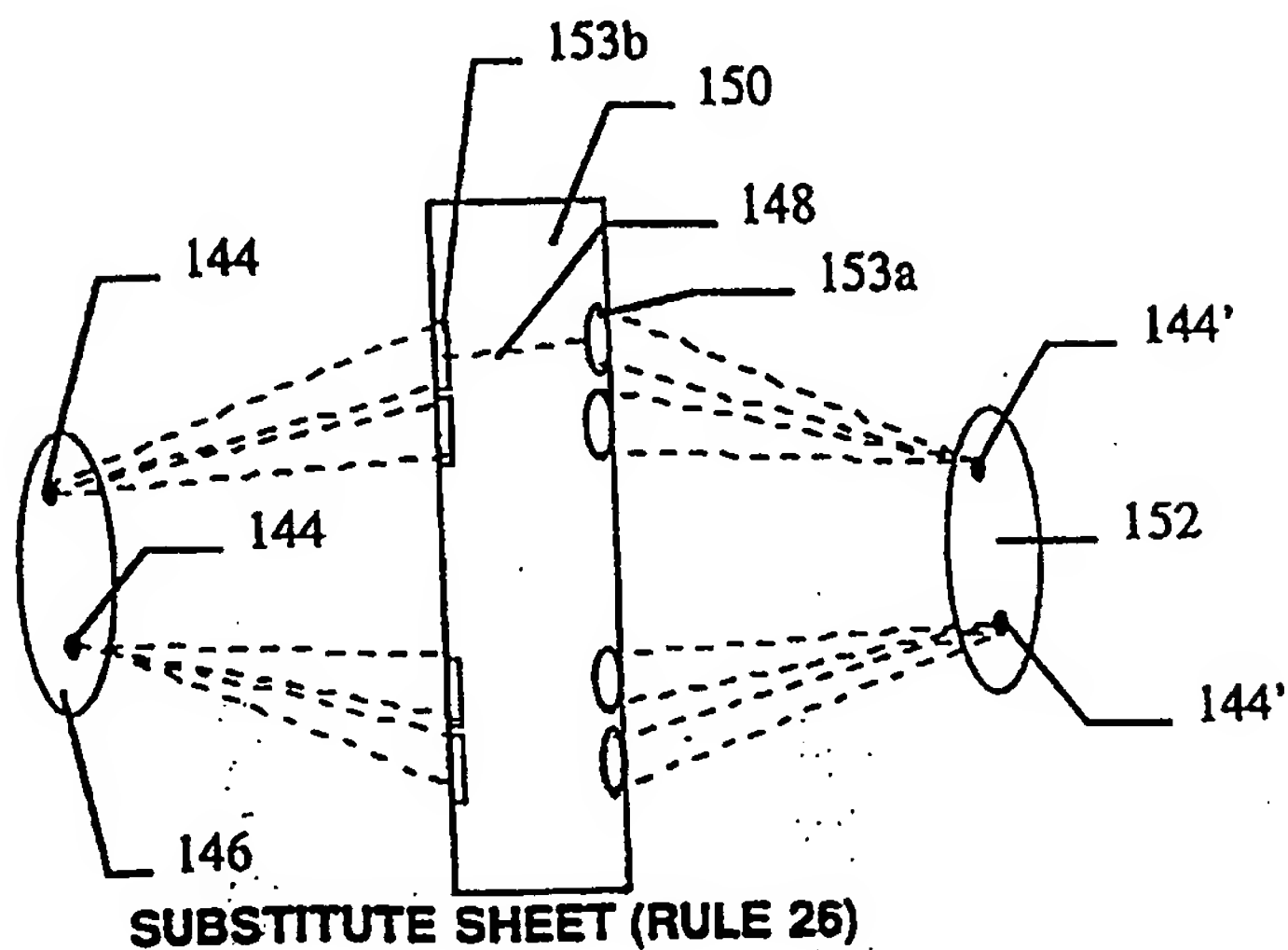


FIG. 6B



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FIG. 7A

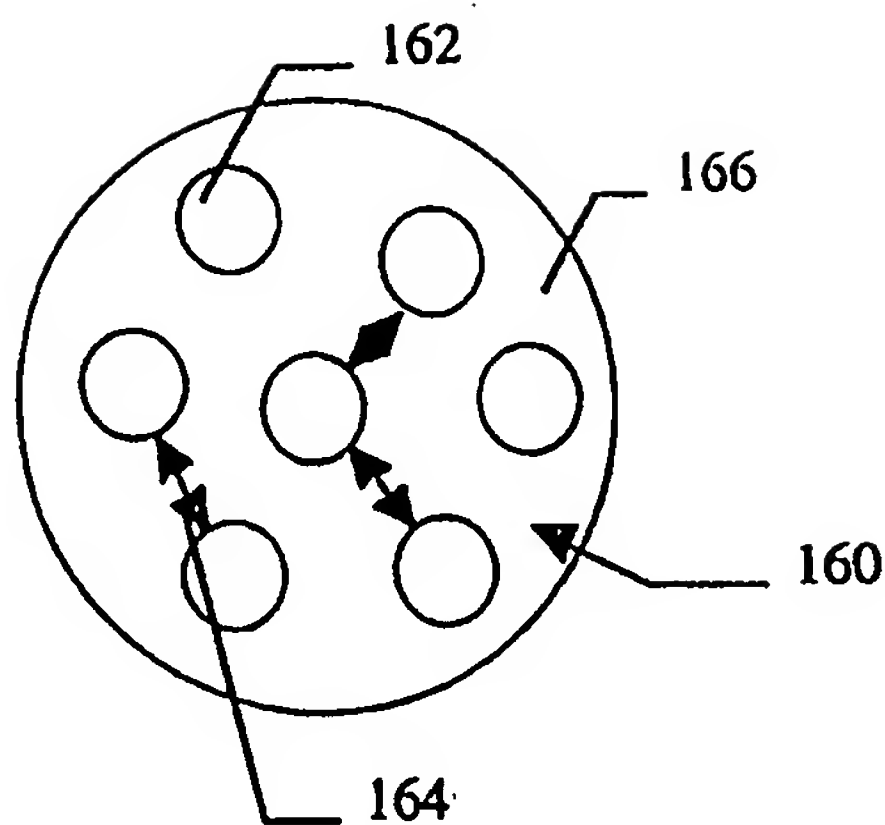


FIG. 7B

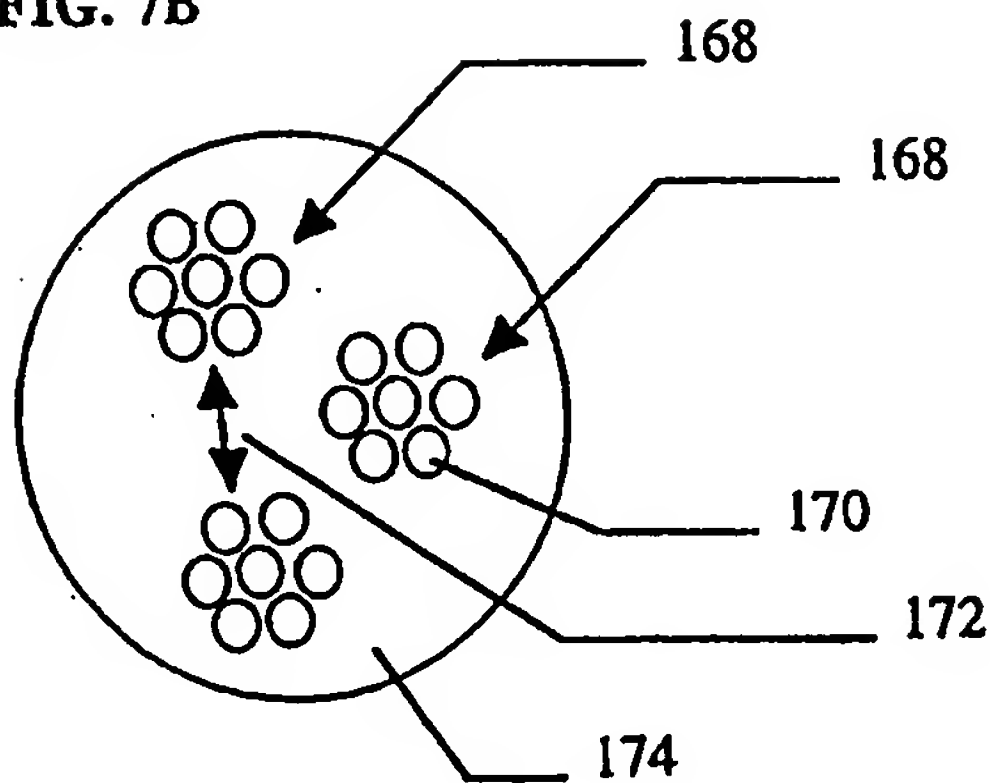


FIG. 7C

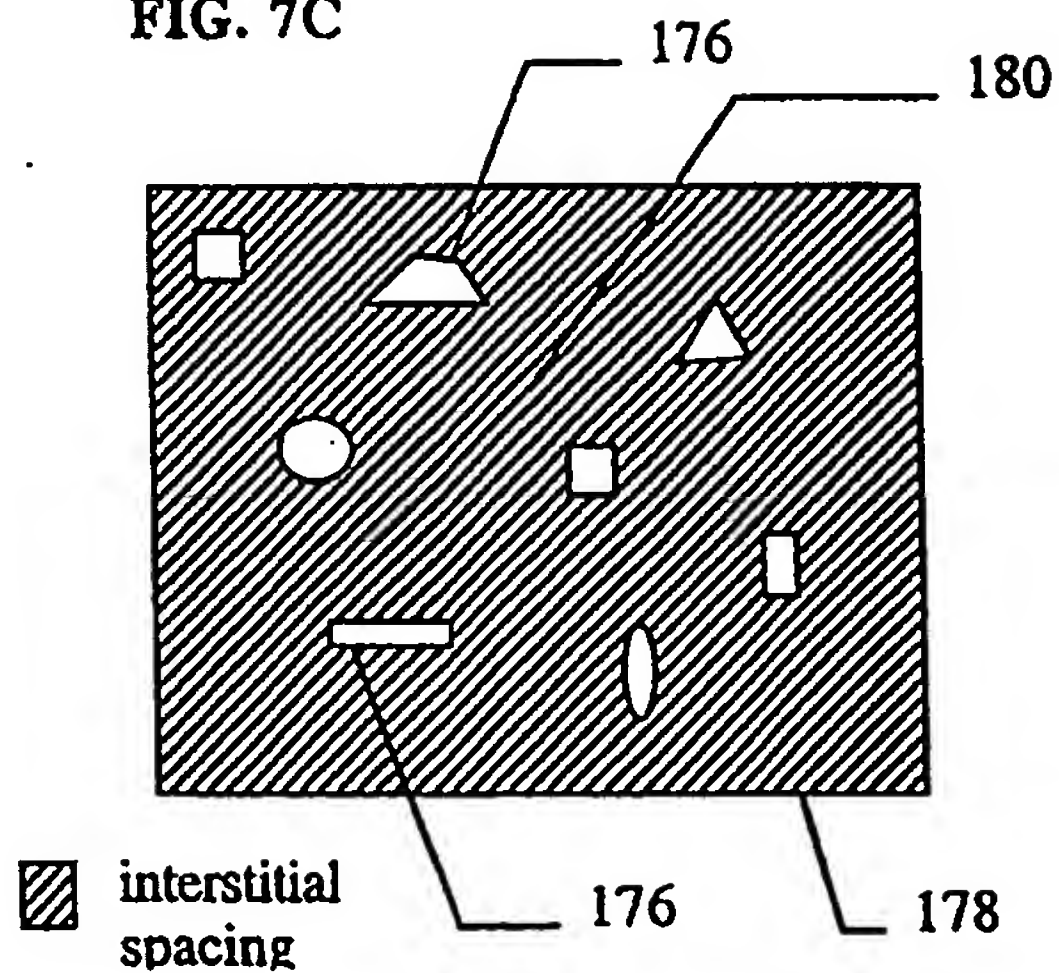


FIG. 7D

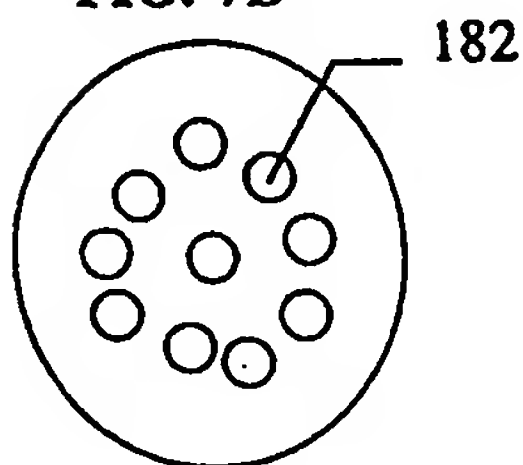
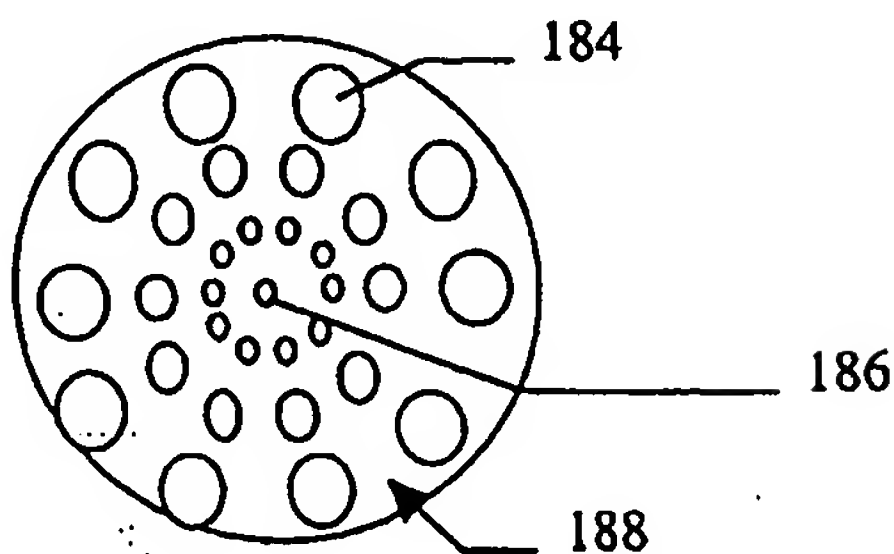


FIG. 7E



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FIG. 8

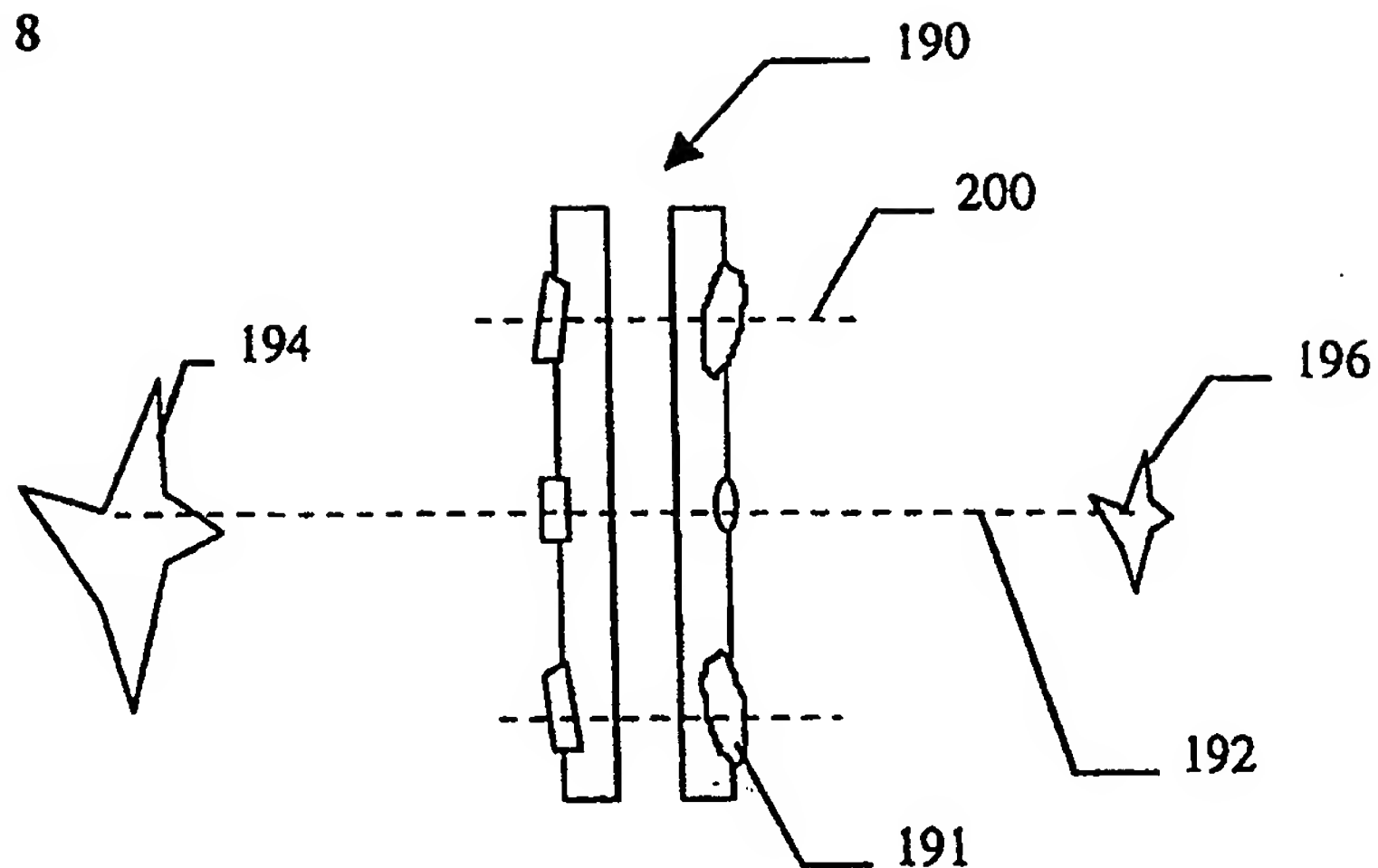
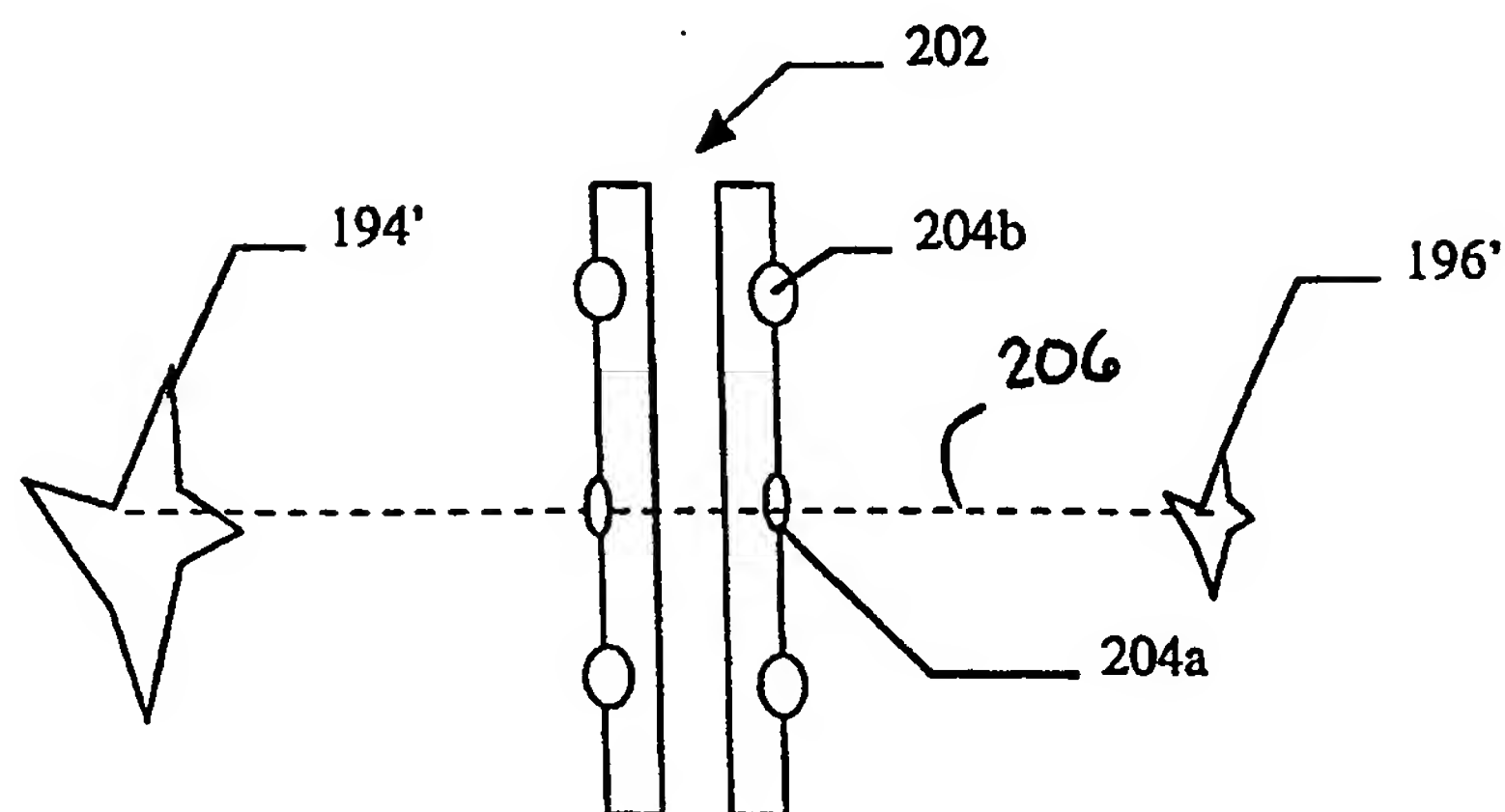


FIG. 8A



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FIG. 9

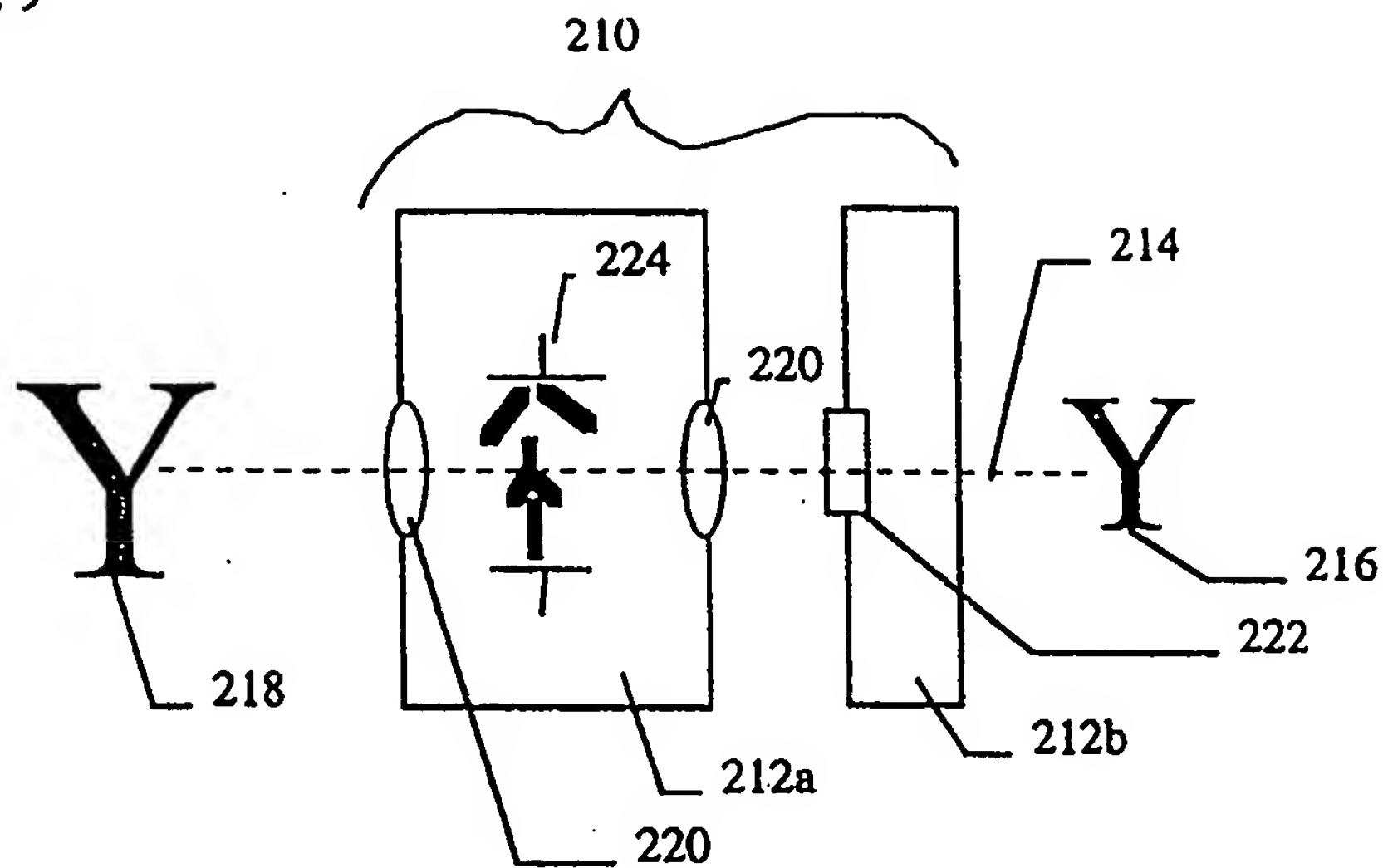
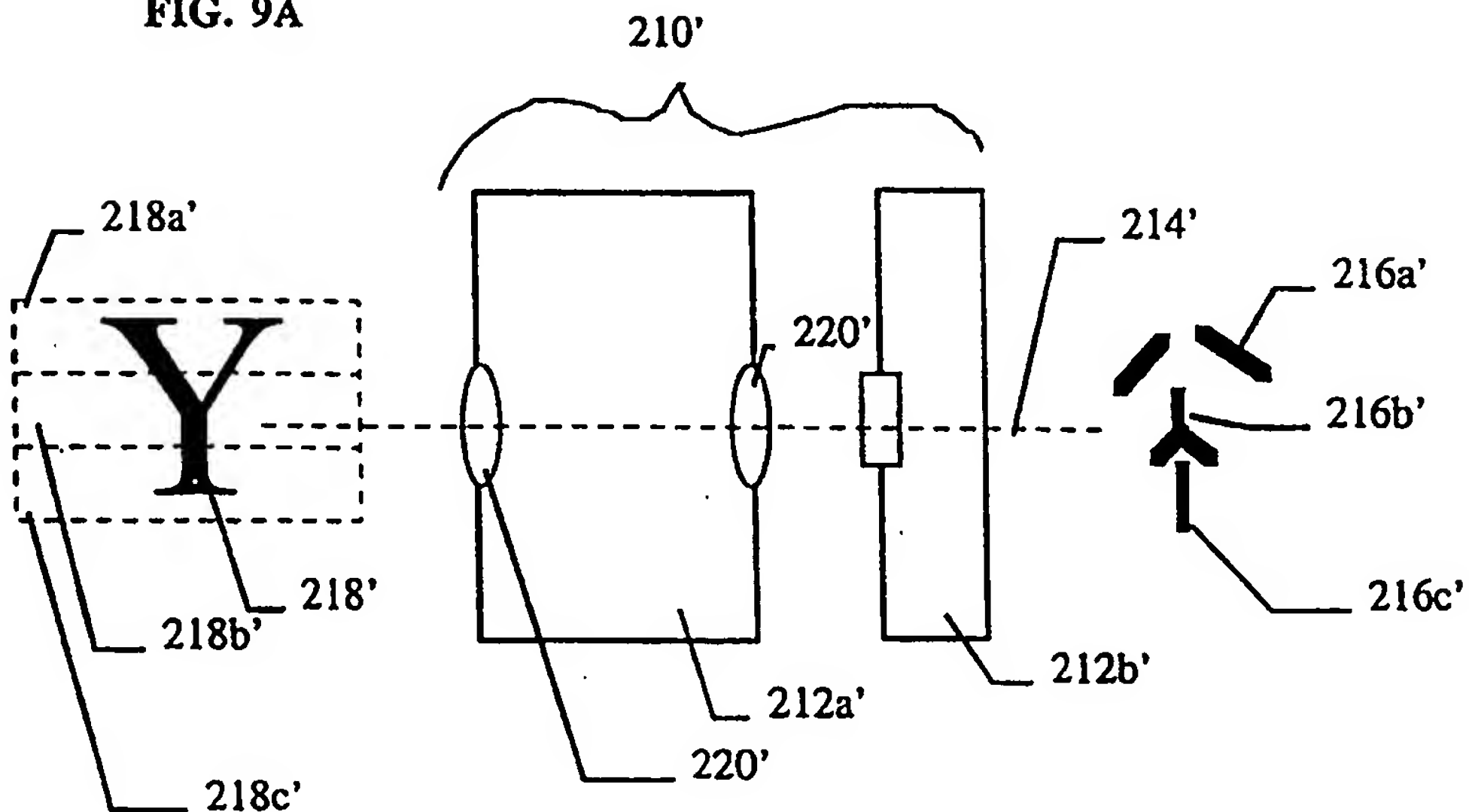


FIG. 9A



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FIG. 10A

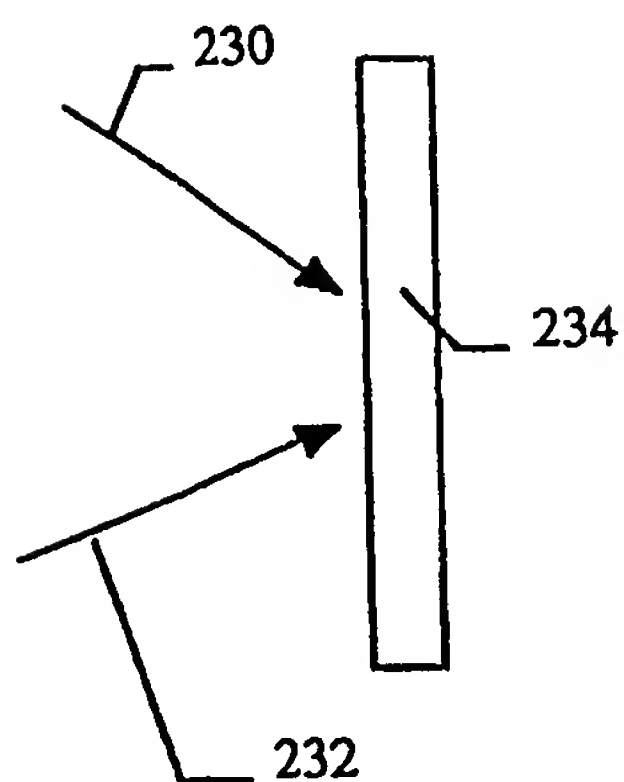


FIG. 10B

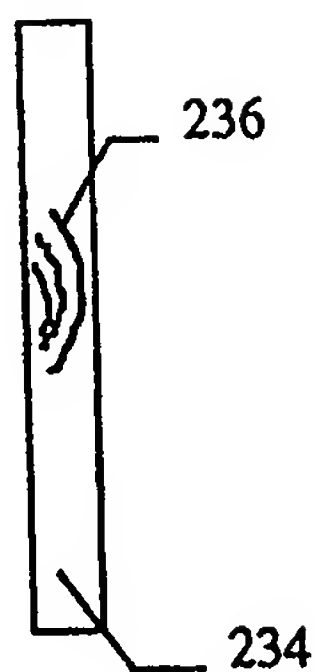


FIG. 10C

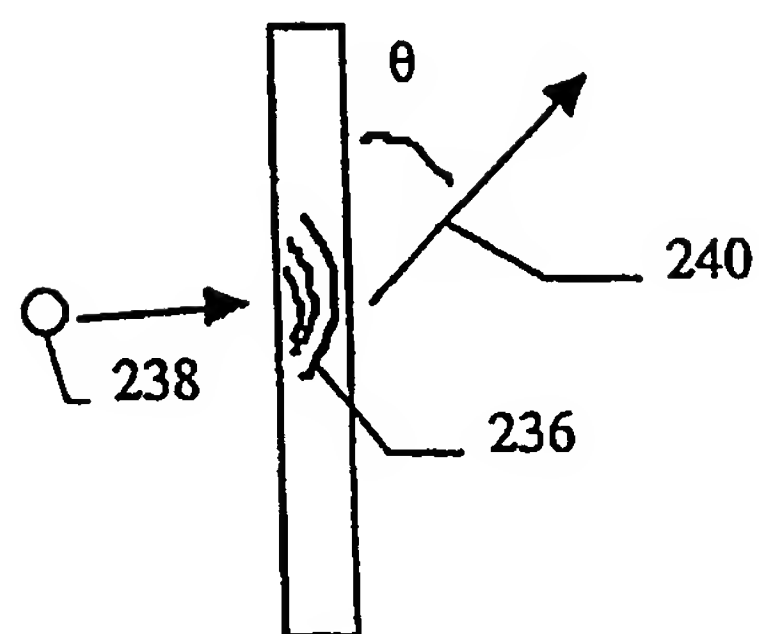


FIG. 11A

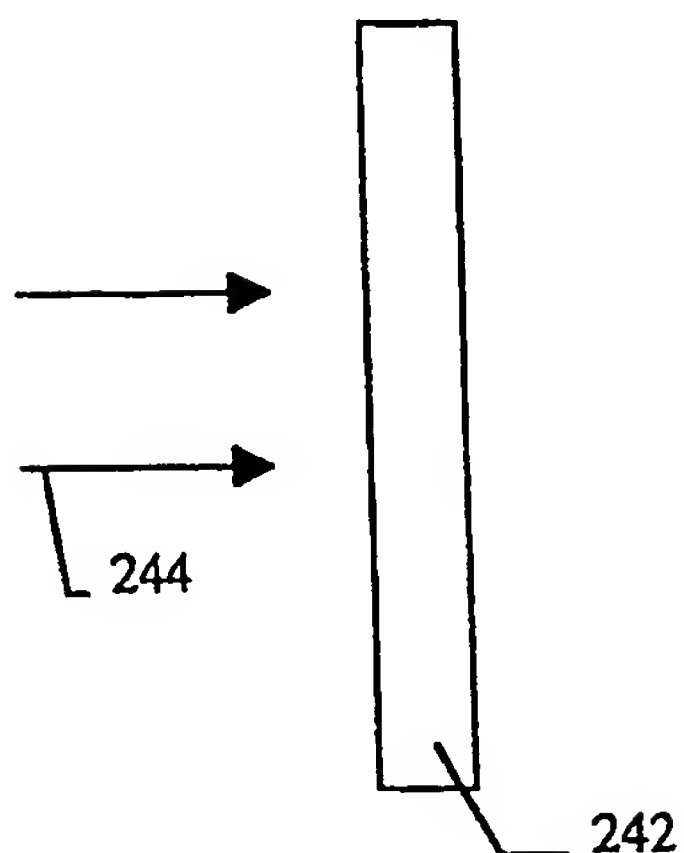
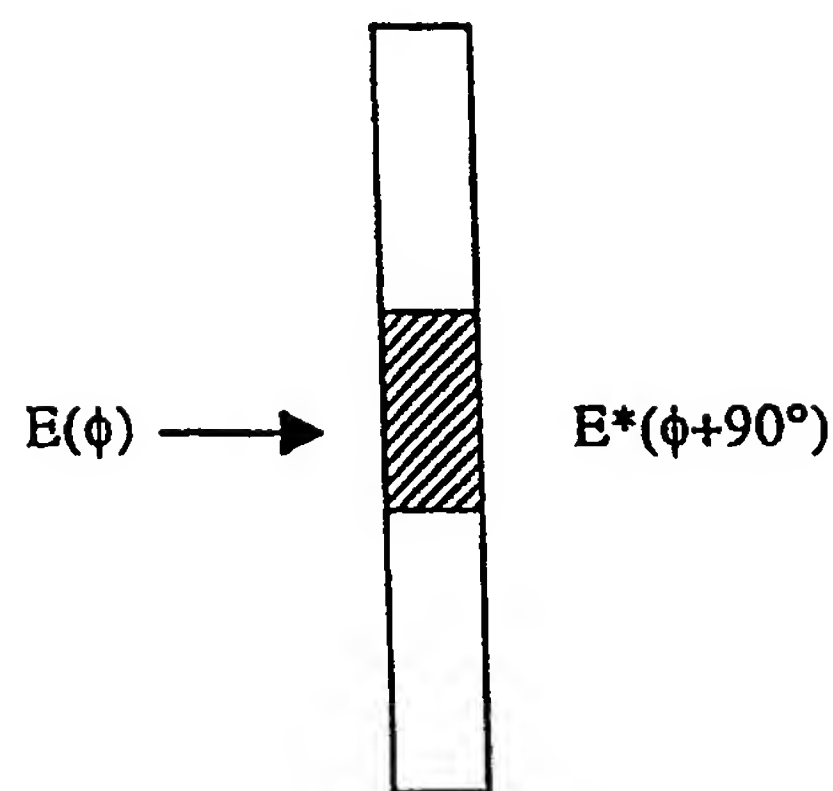


FIG. 11B



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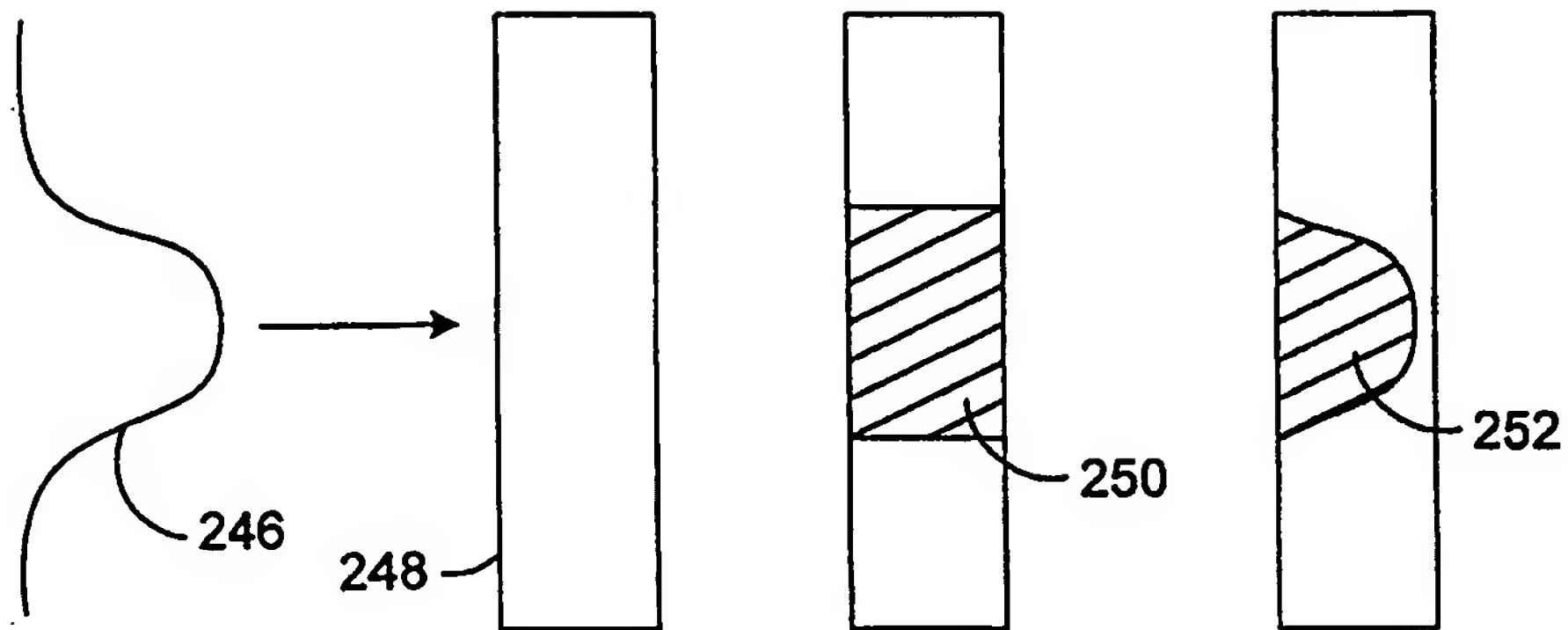


Fig. 12A

Fig. 12B

Fig. 12C

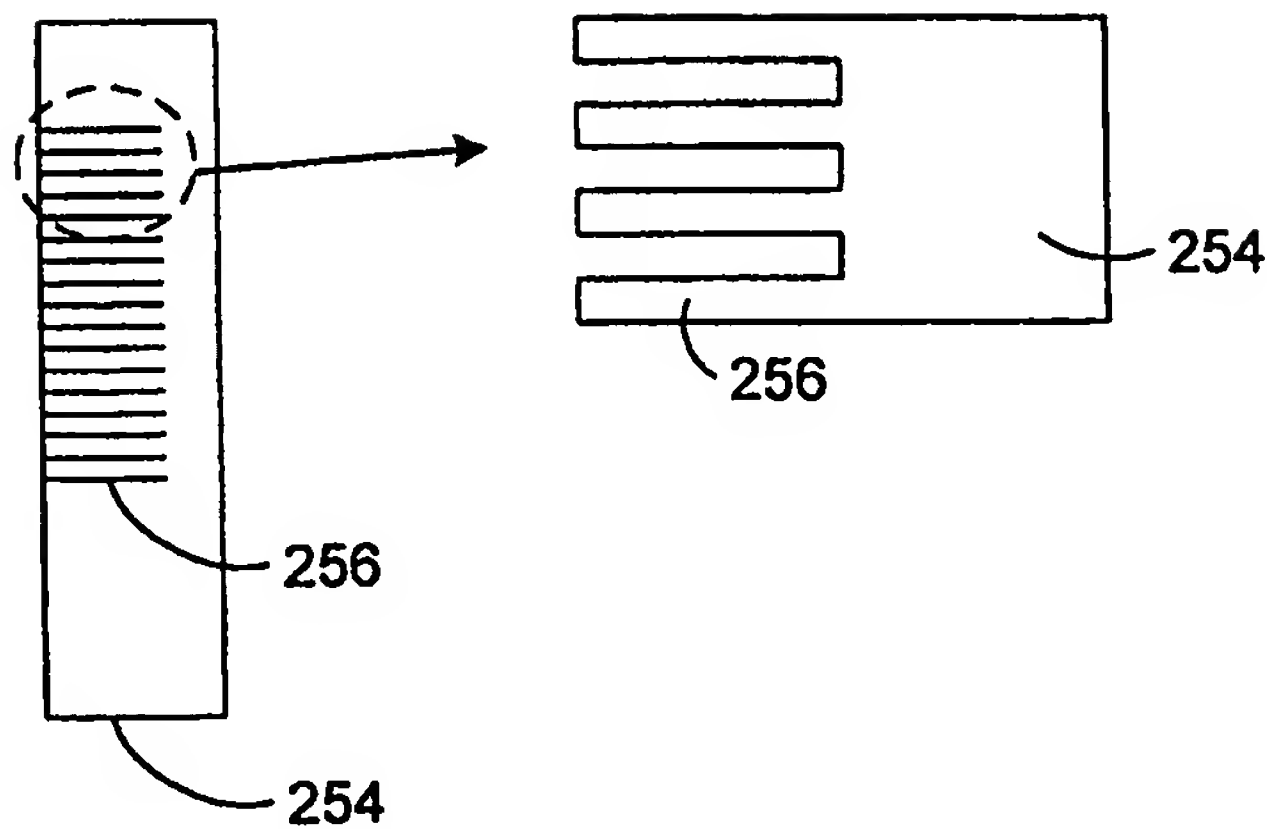


Fig. 12D

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FIG. 13A

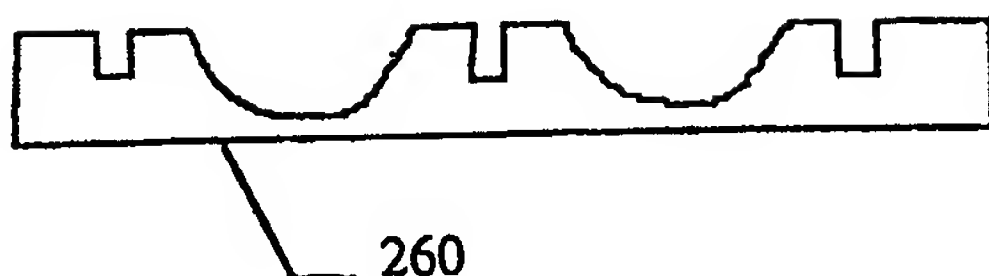


FIG. 13B

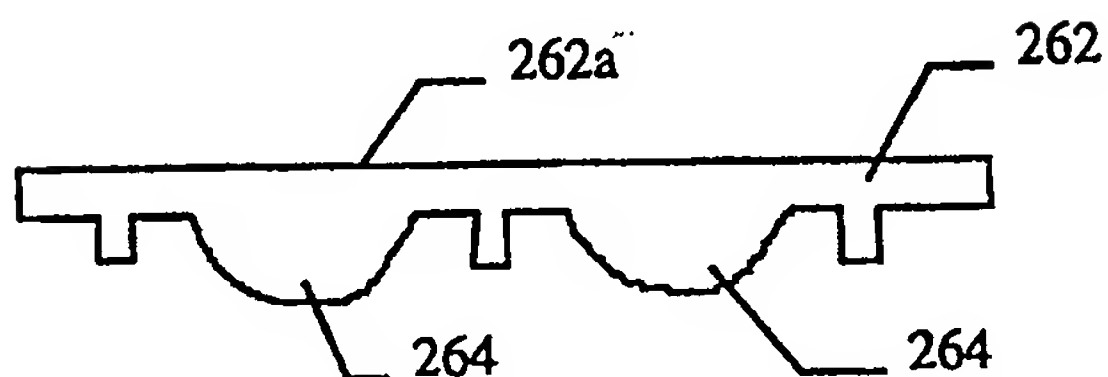


FIG. 14A



FIG. 14B

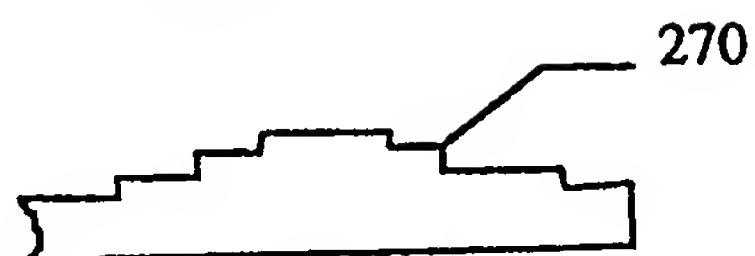


FIG. 15A

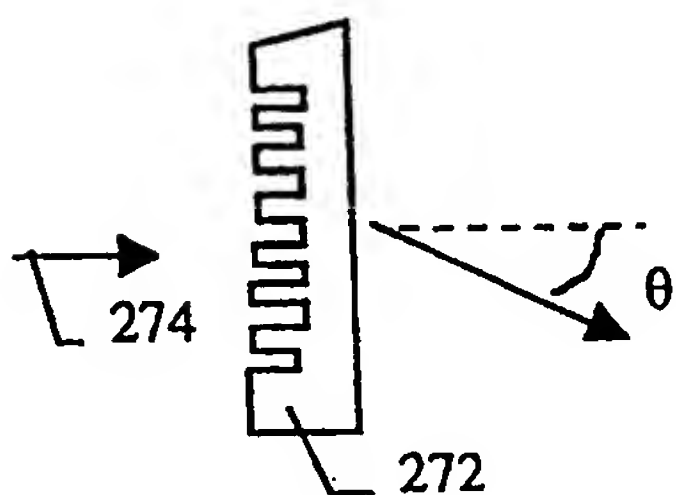


FIG. 15B

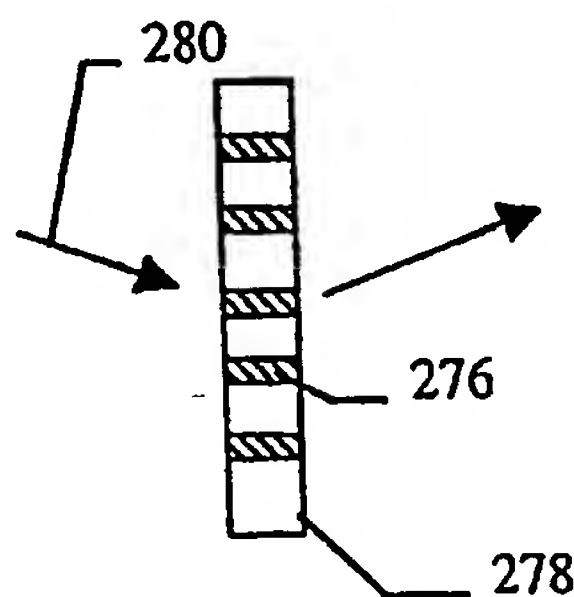
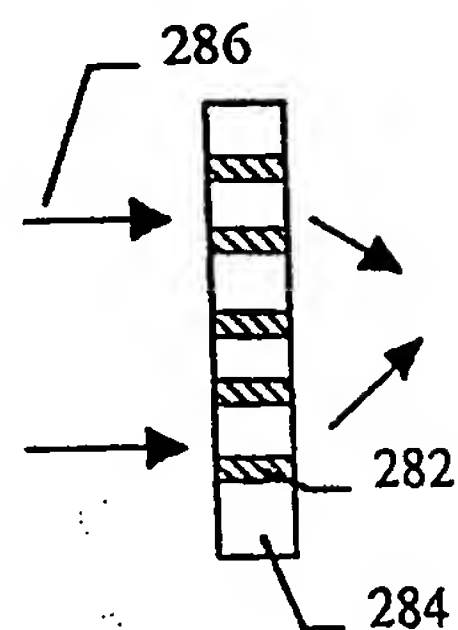


FIG. 15C



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FIG. 15D

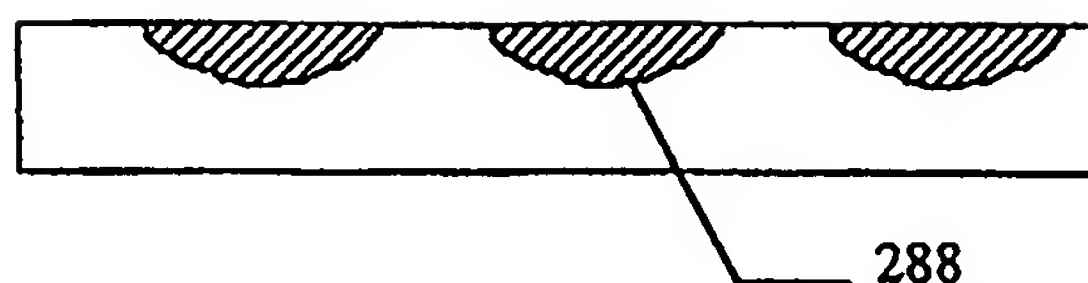


FIG. 15E

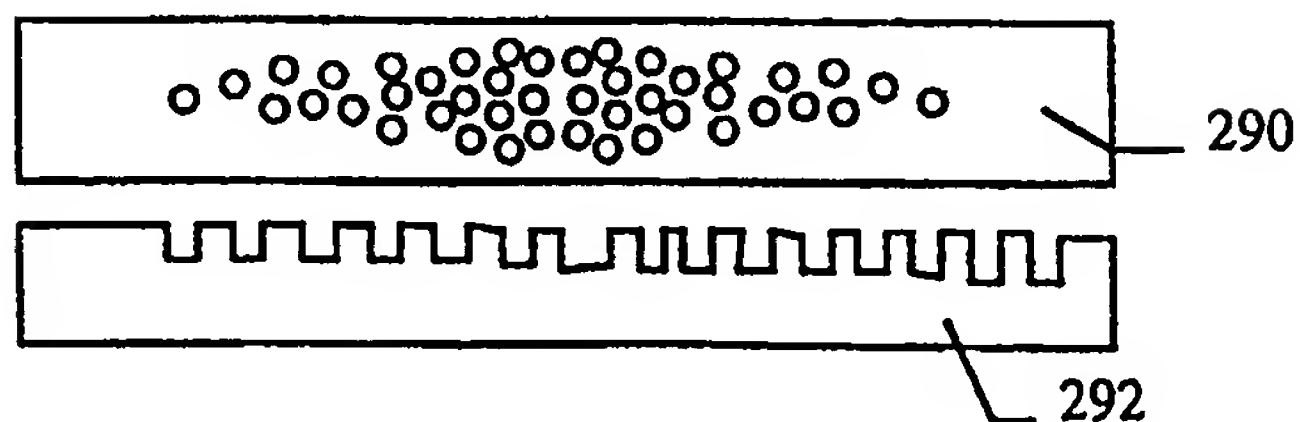


FIG. 15F

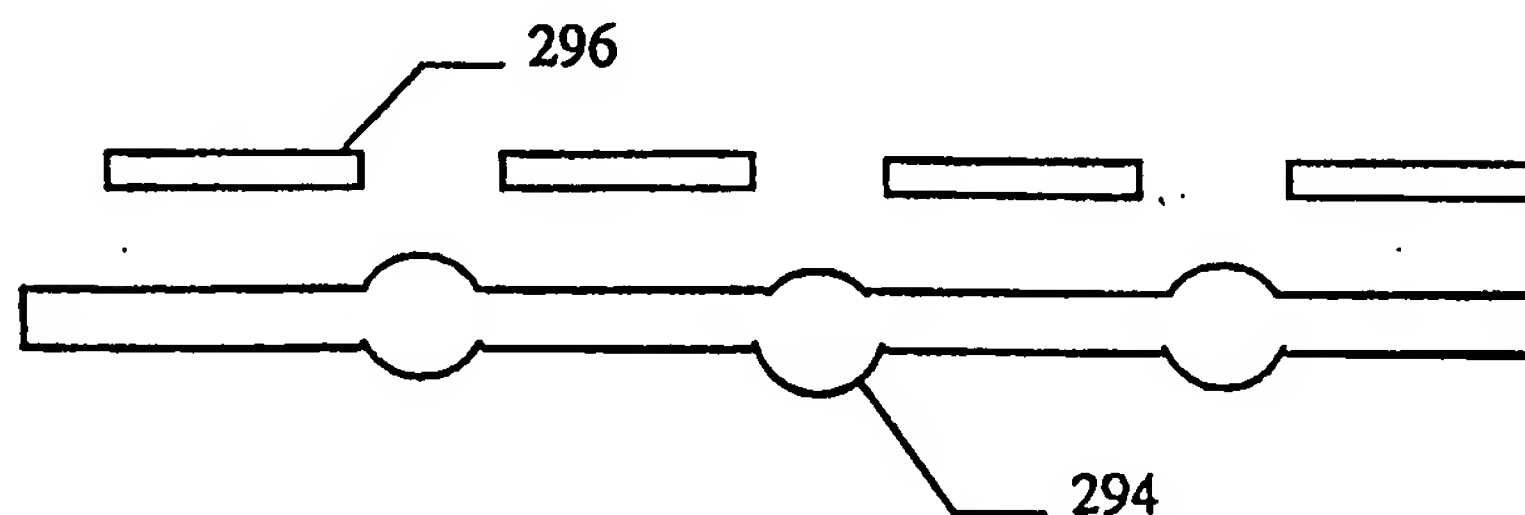
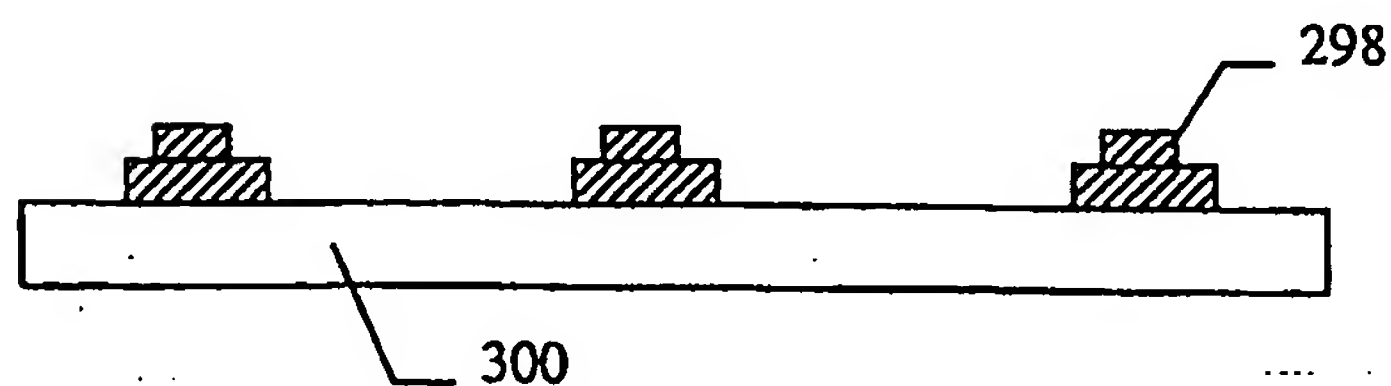
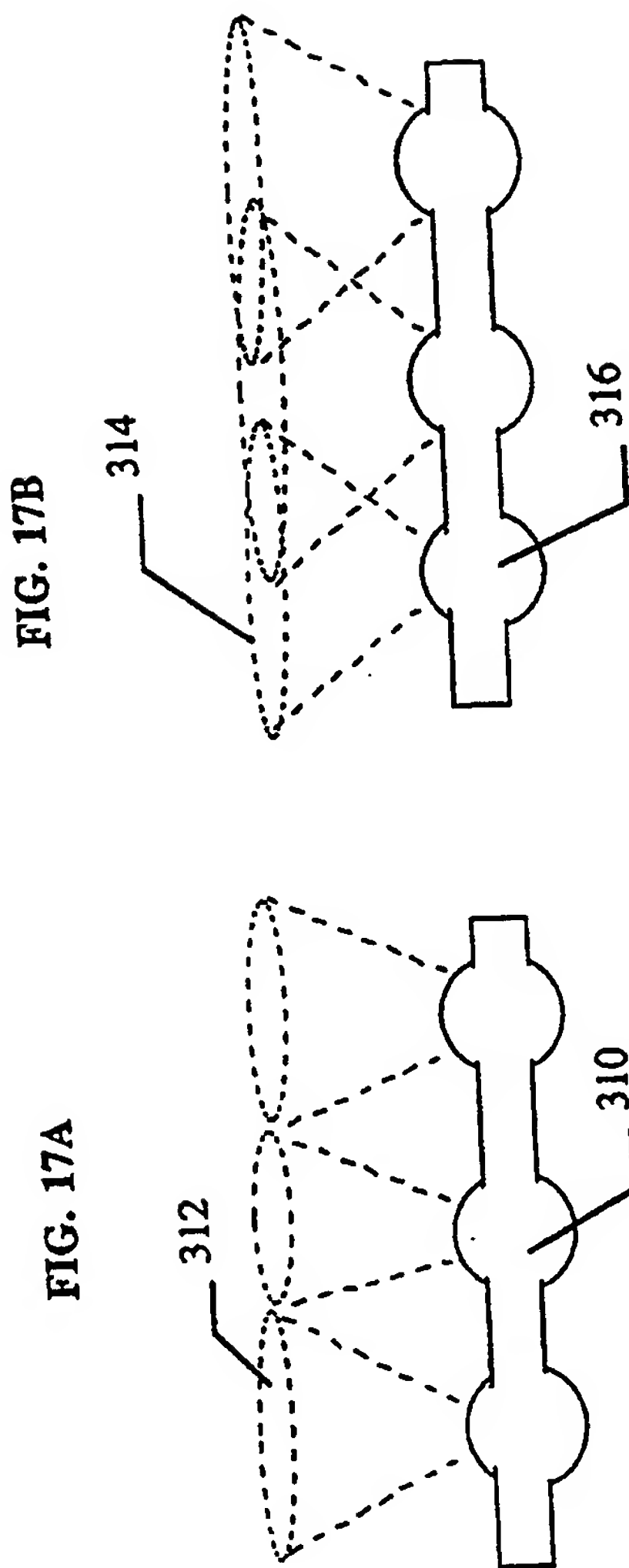
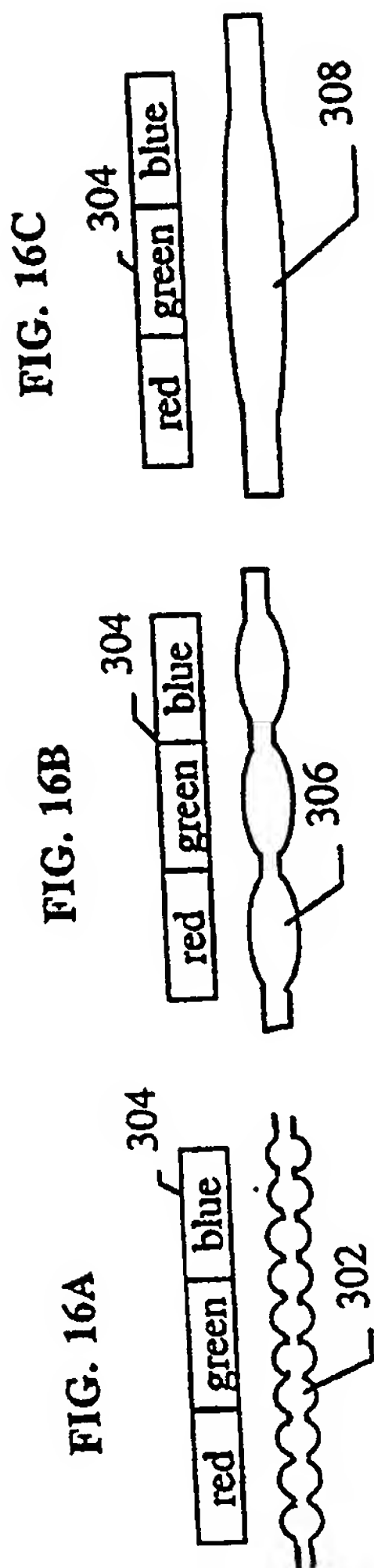


FIG. 15G





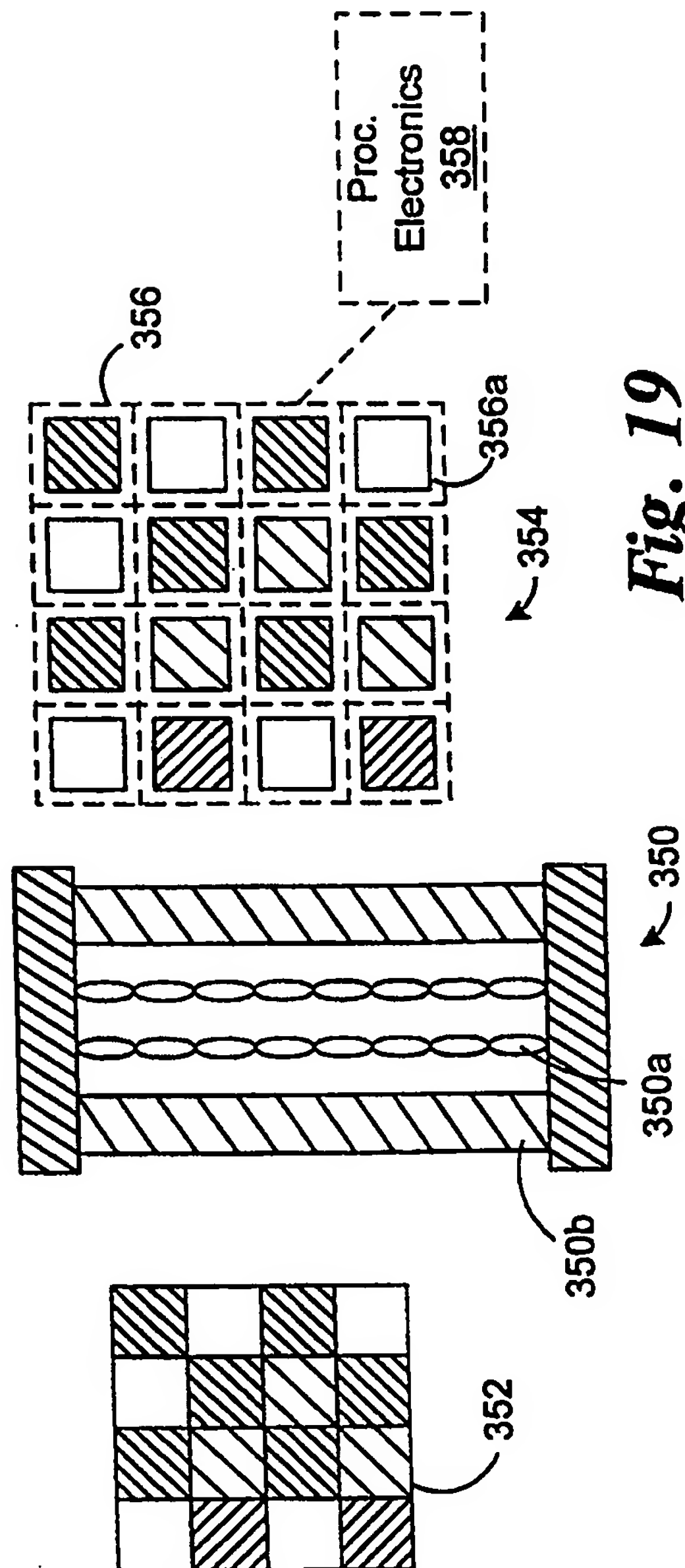
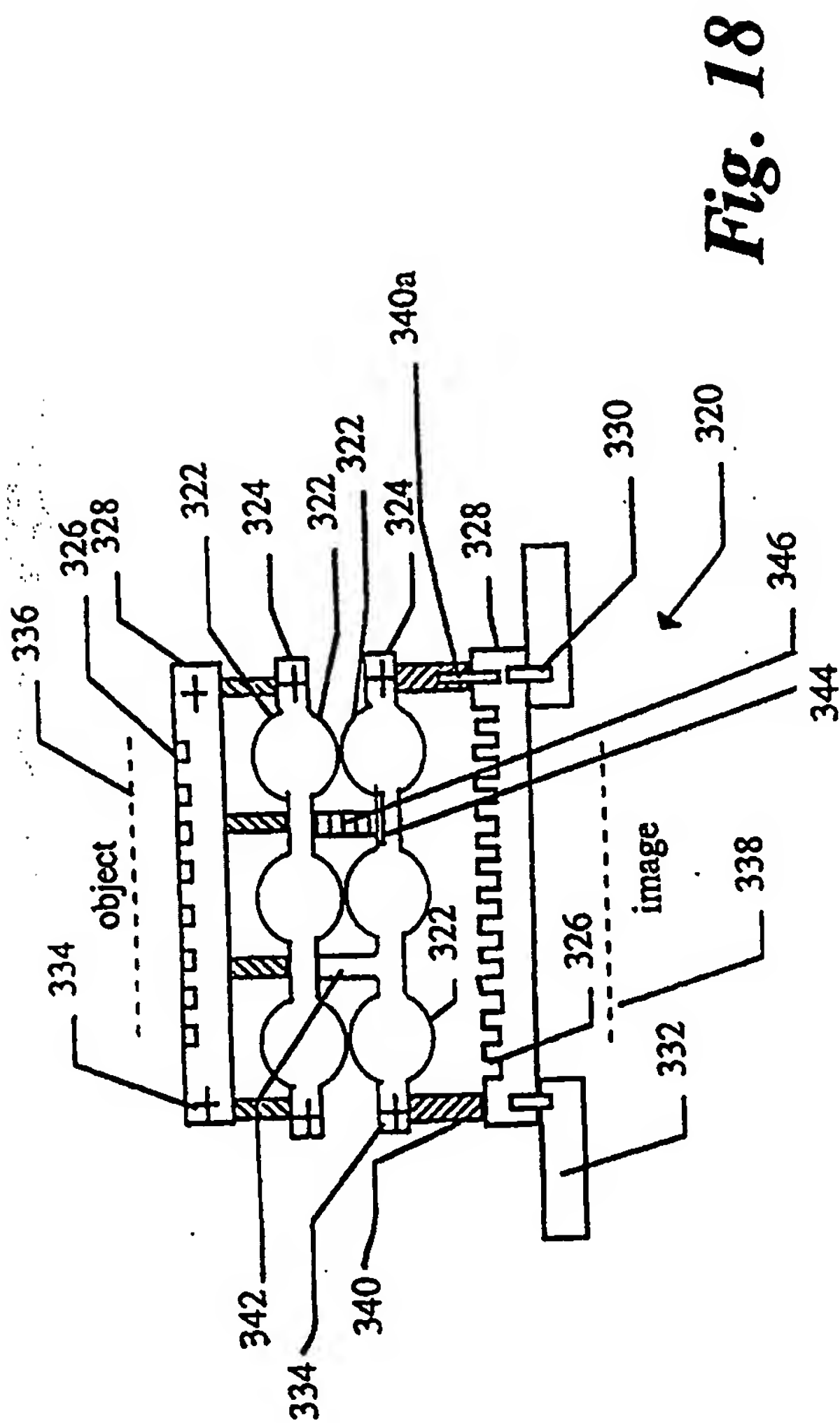


FIG. 20

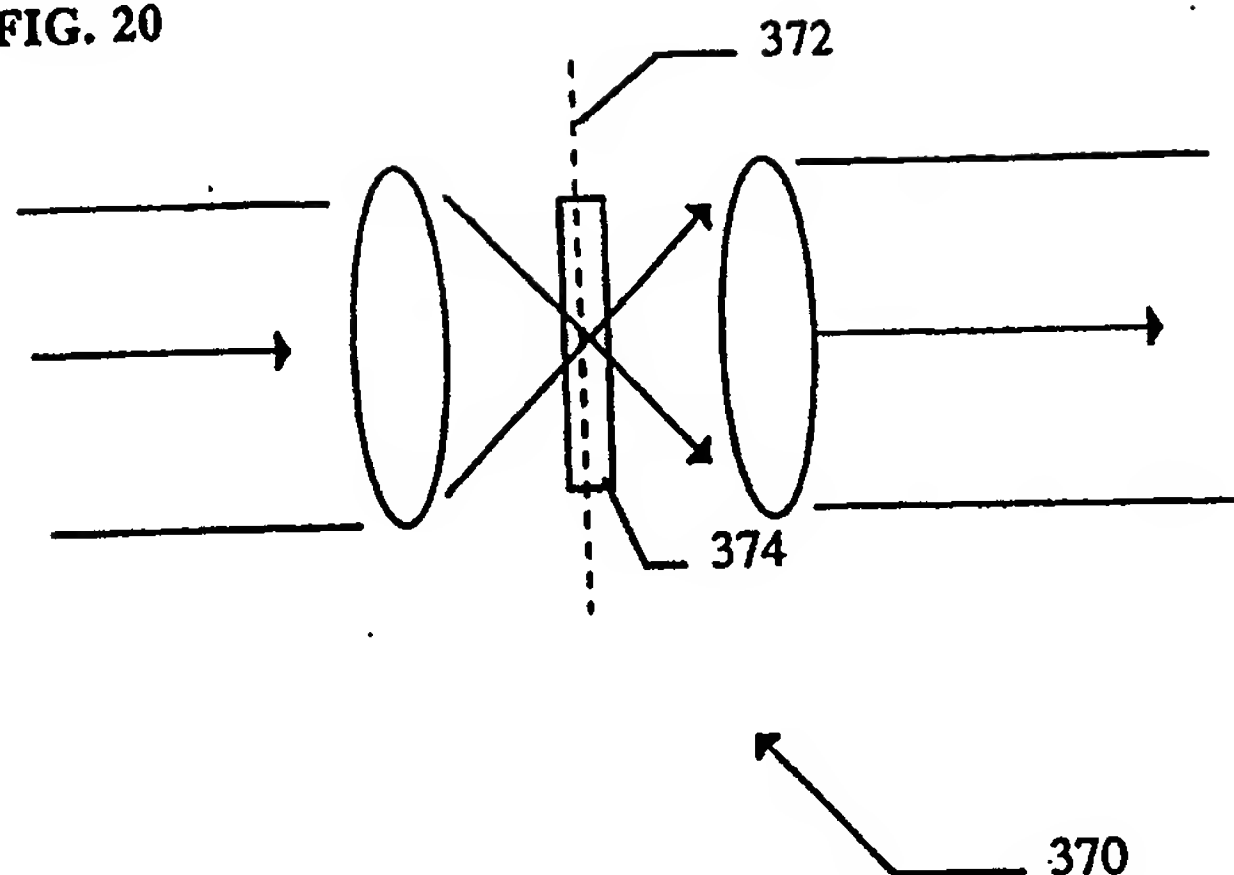


FIG. 21

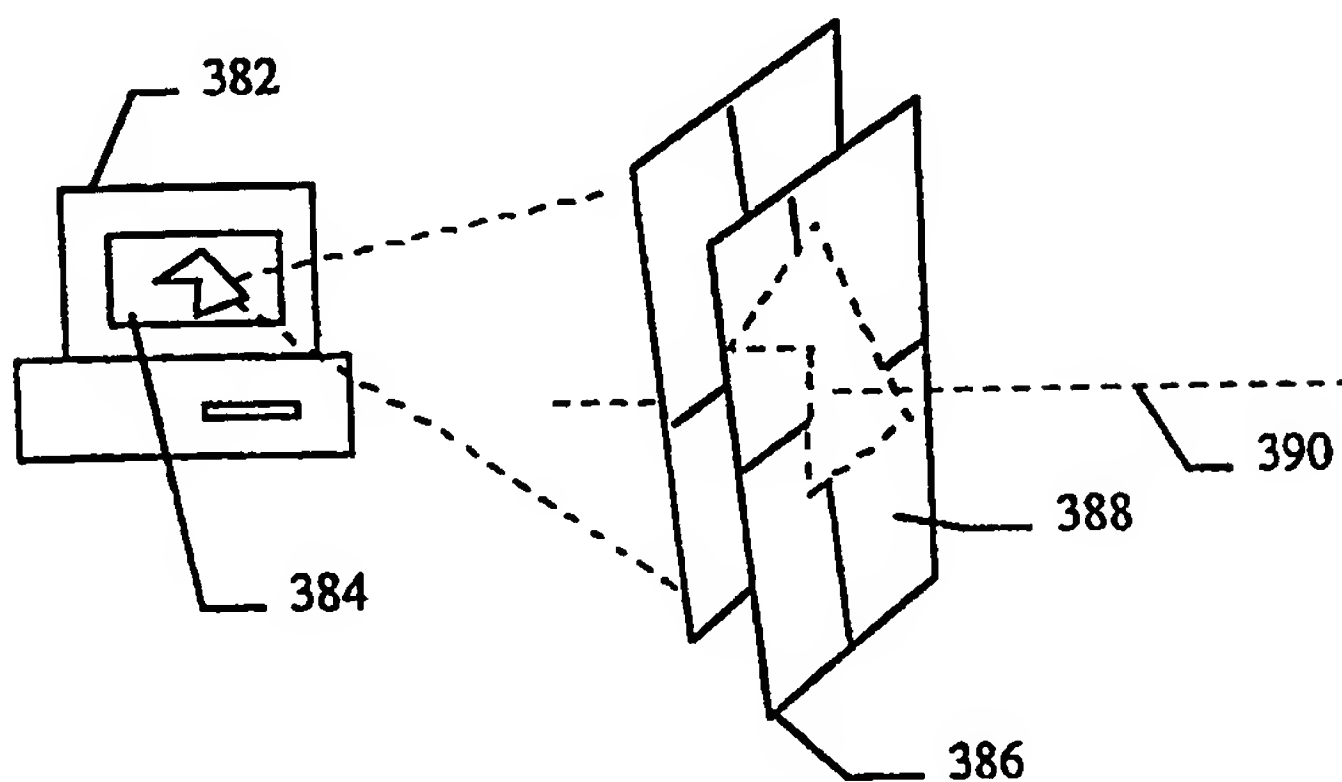
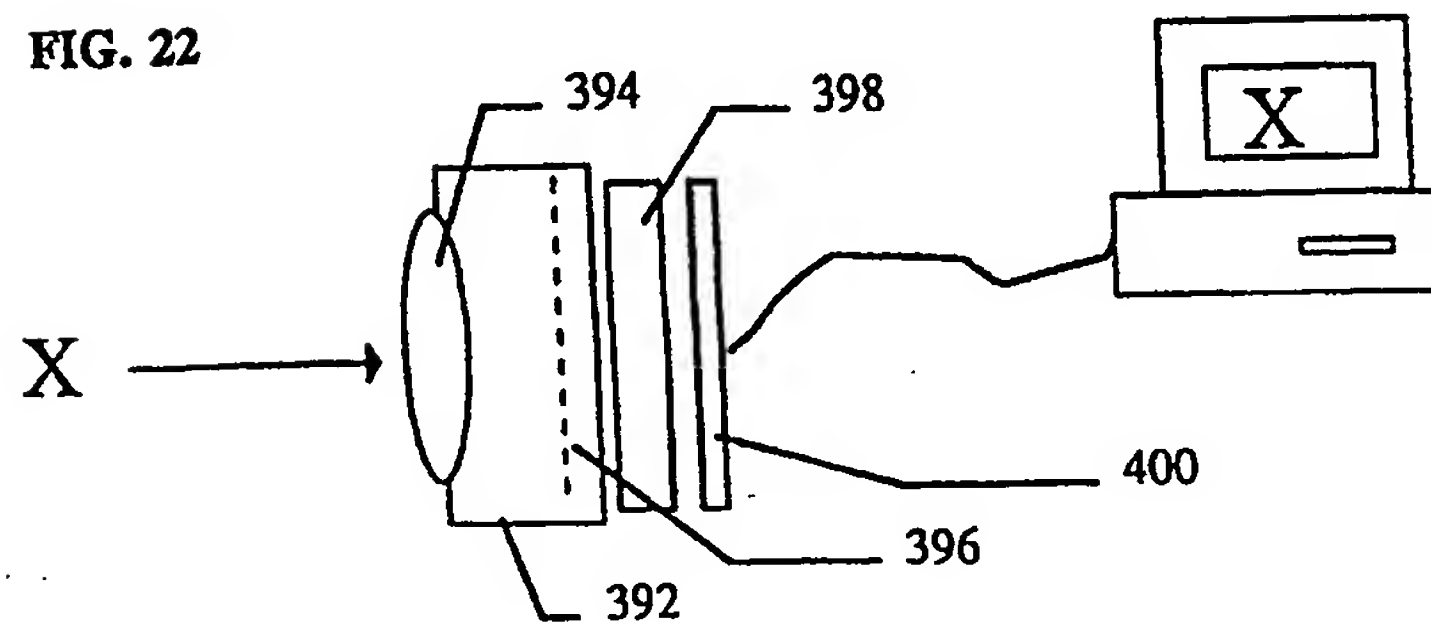


FIG. 22



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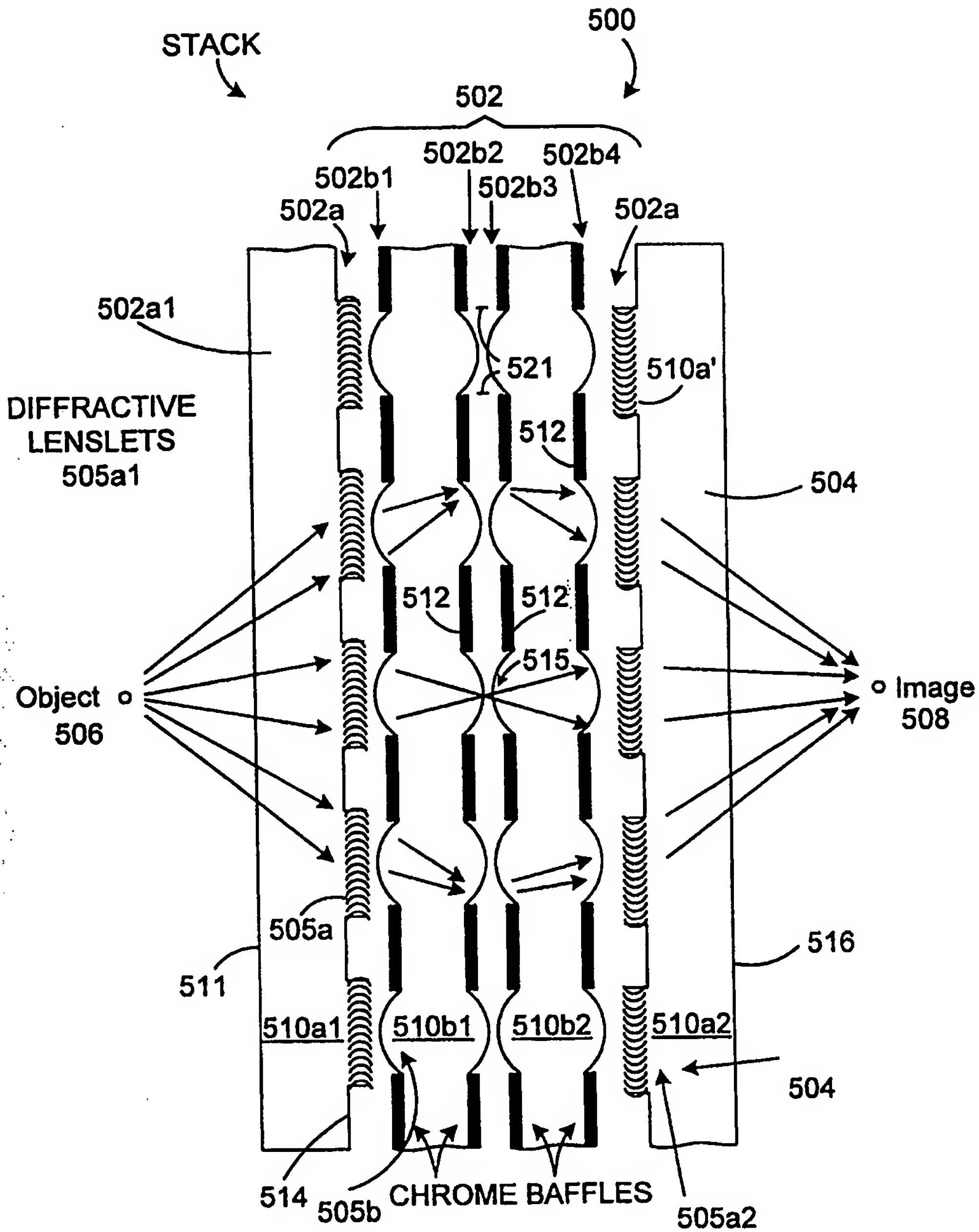


Fig. 23

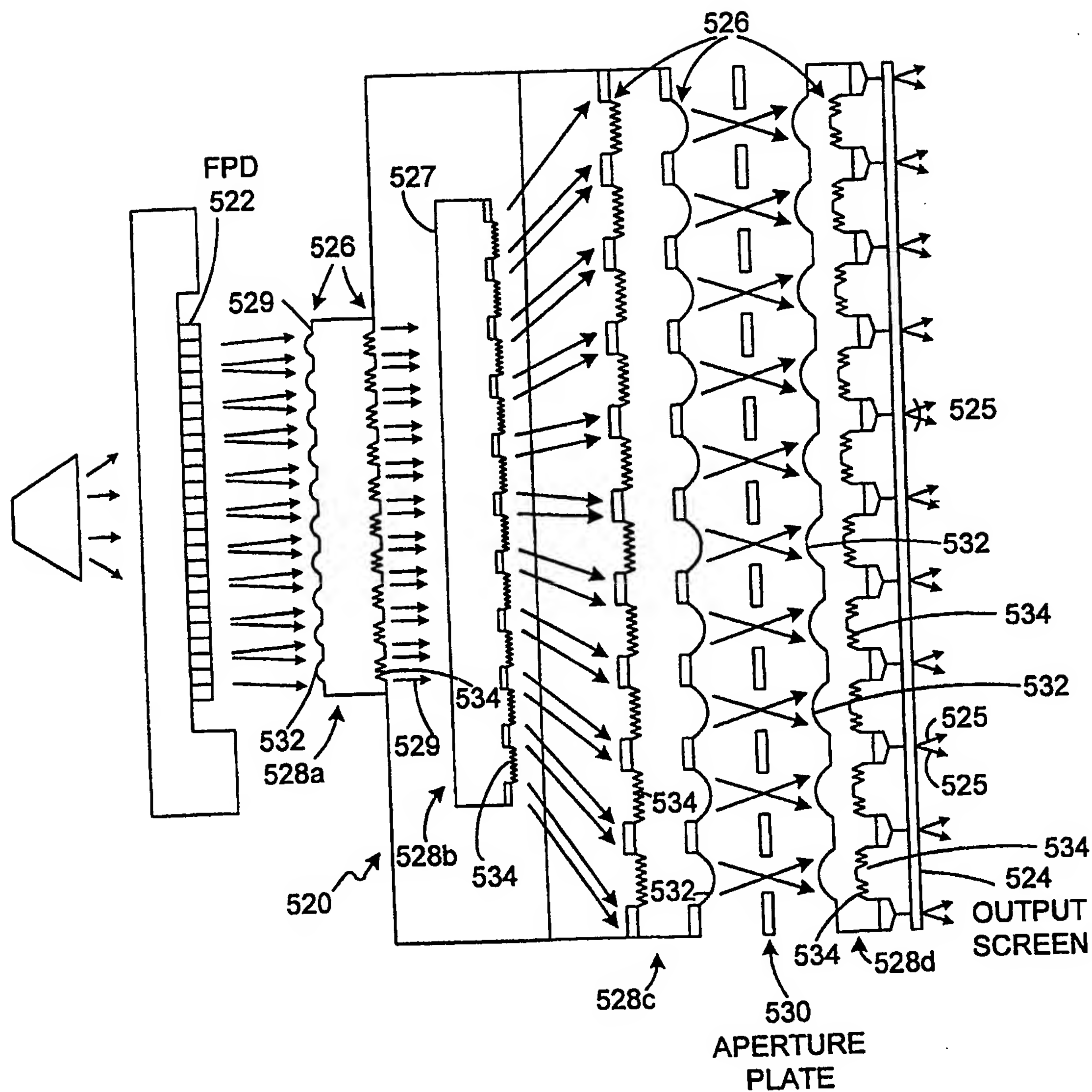


Fig. 24

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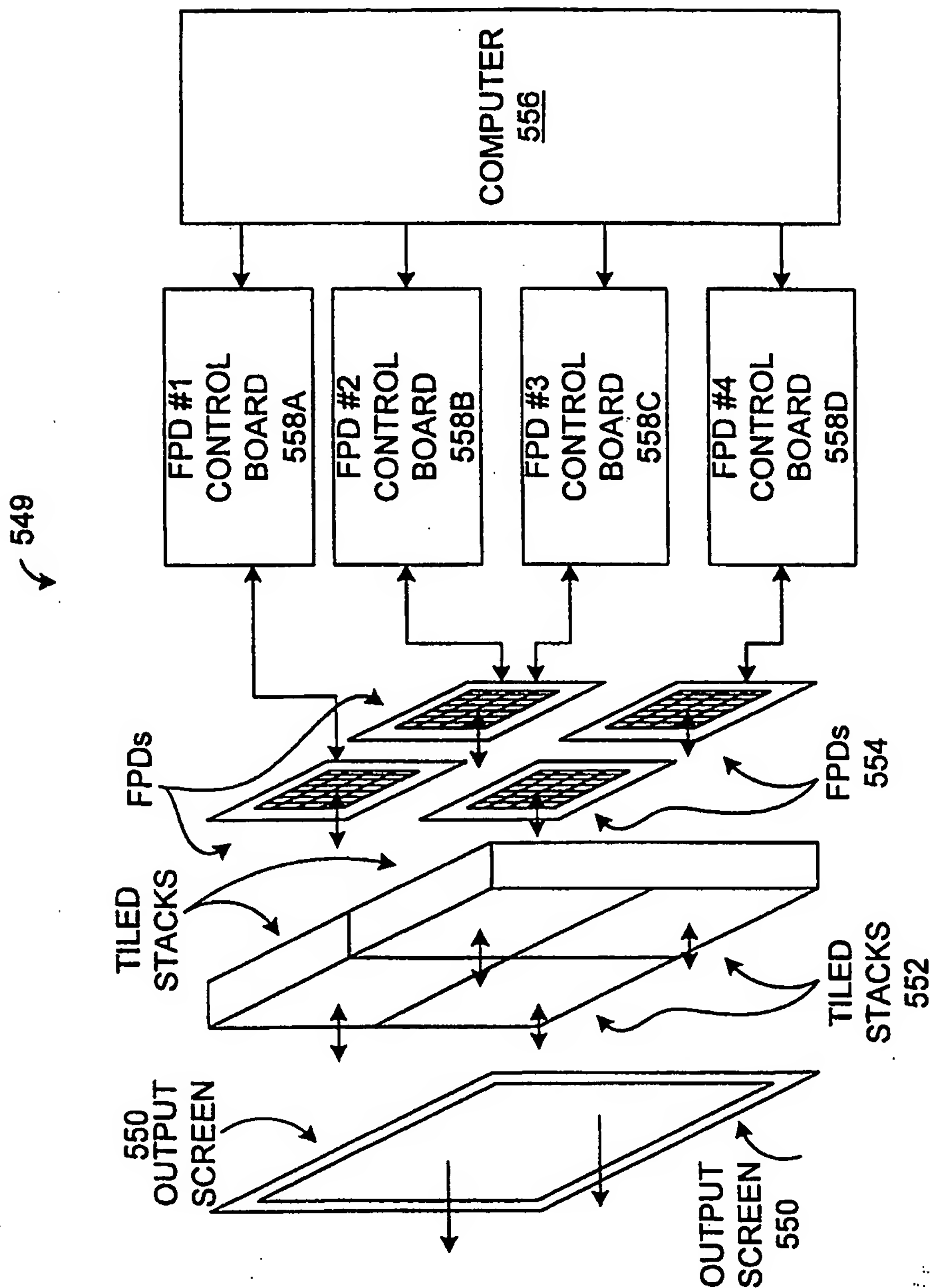


Fig. 25

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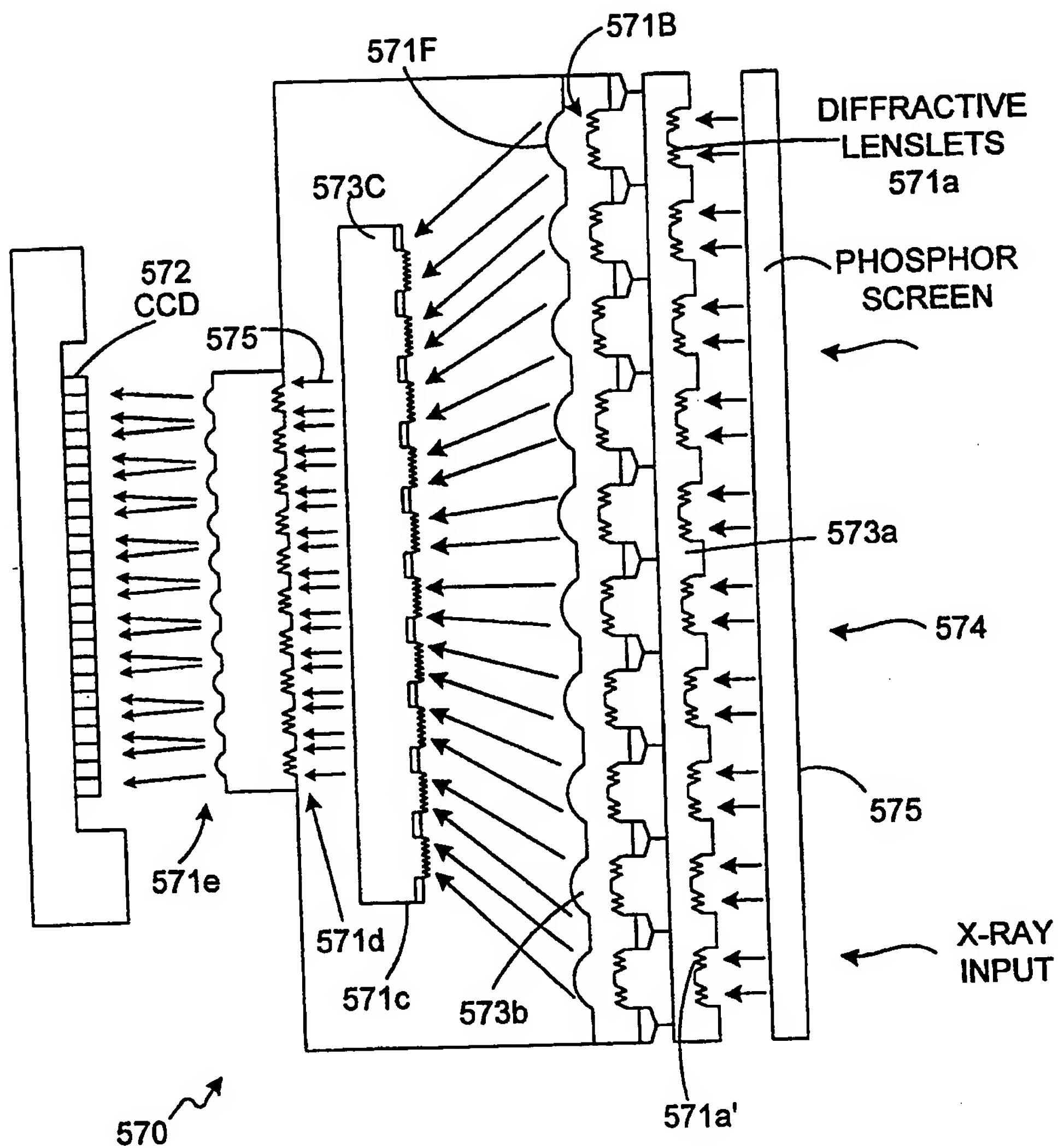


Fig. 26

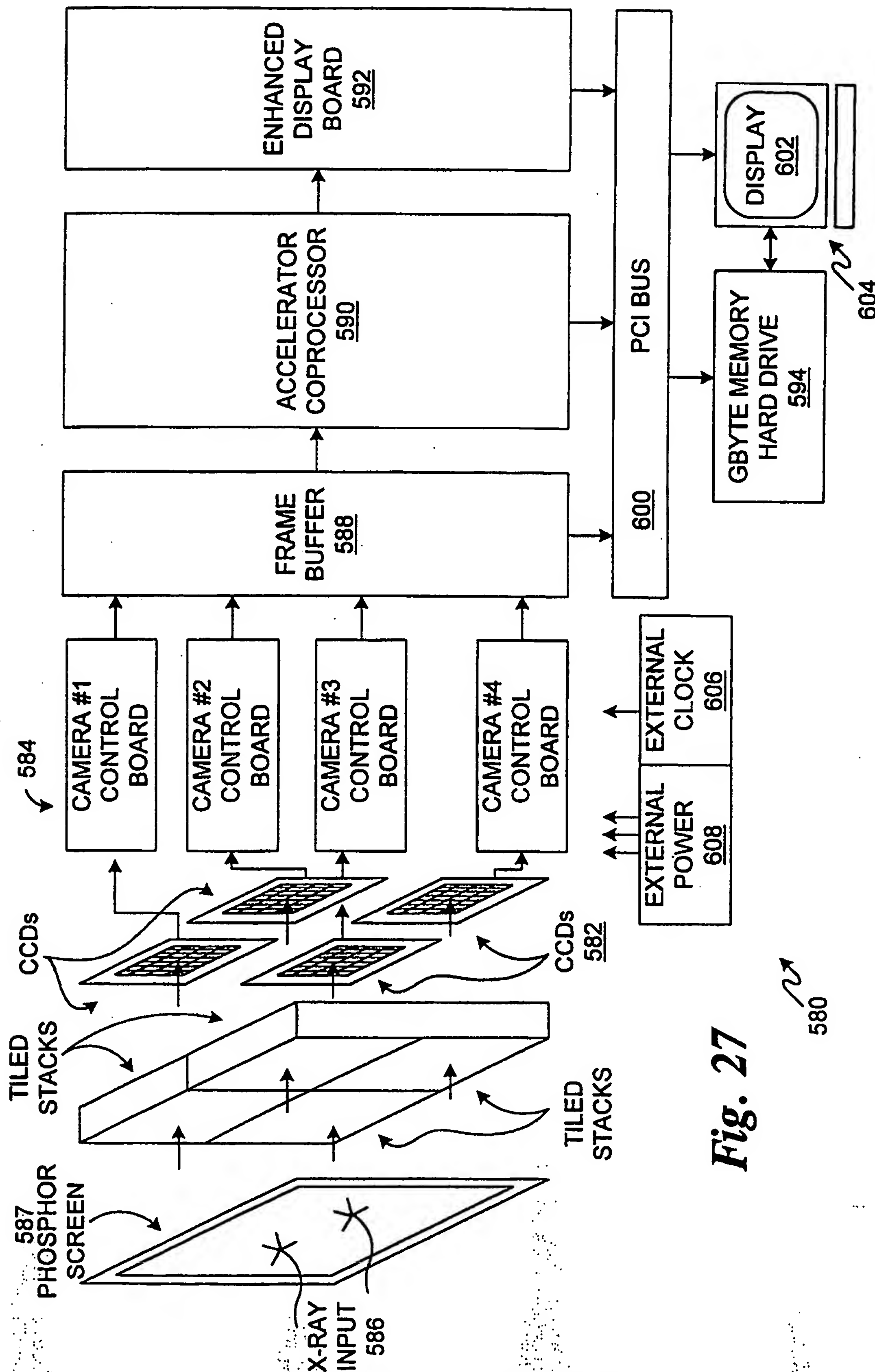


Fig. 27

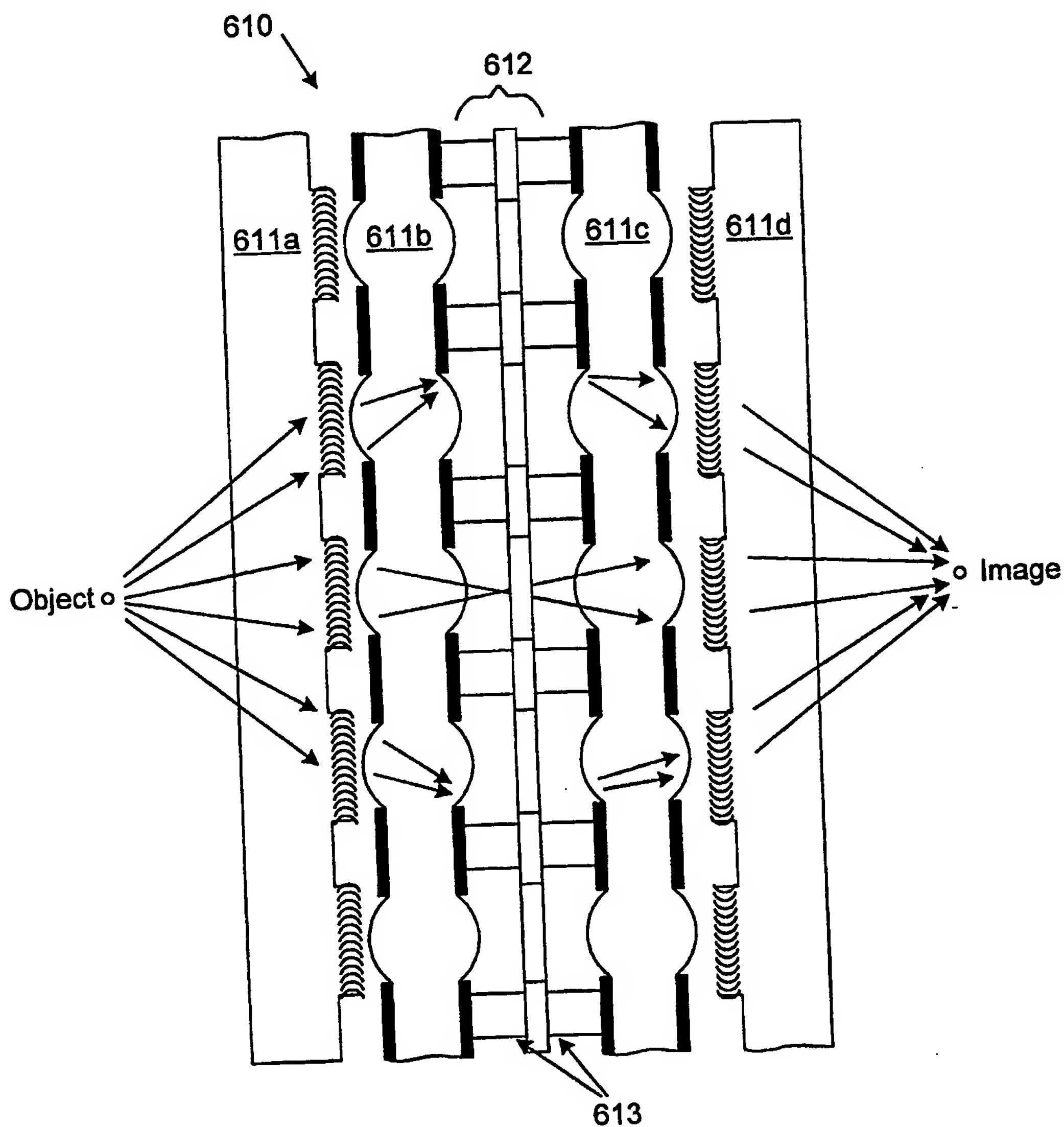


Fig. 28

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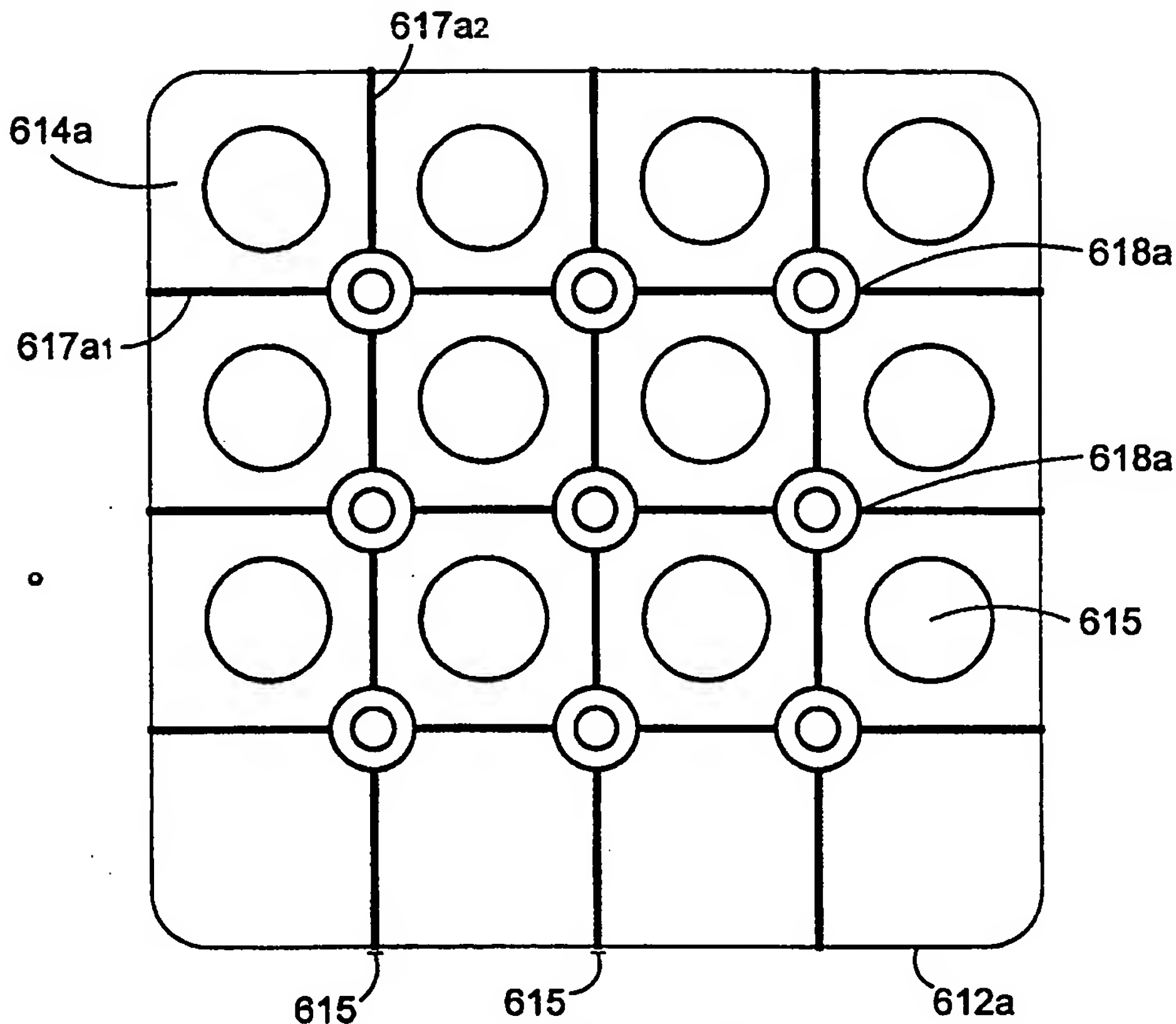


Fig. 28A

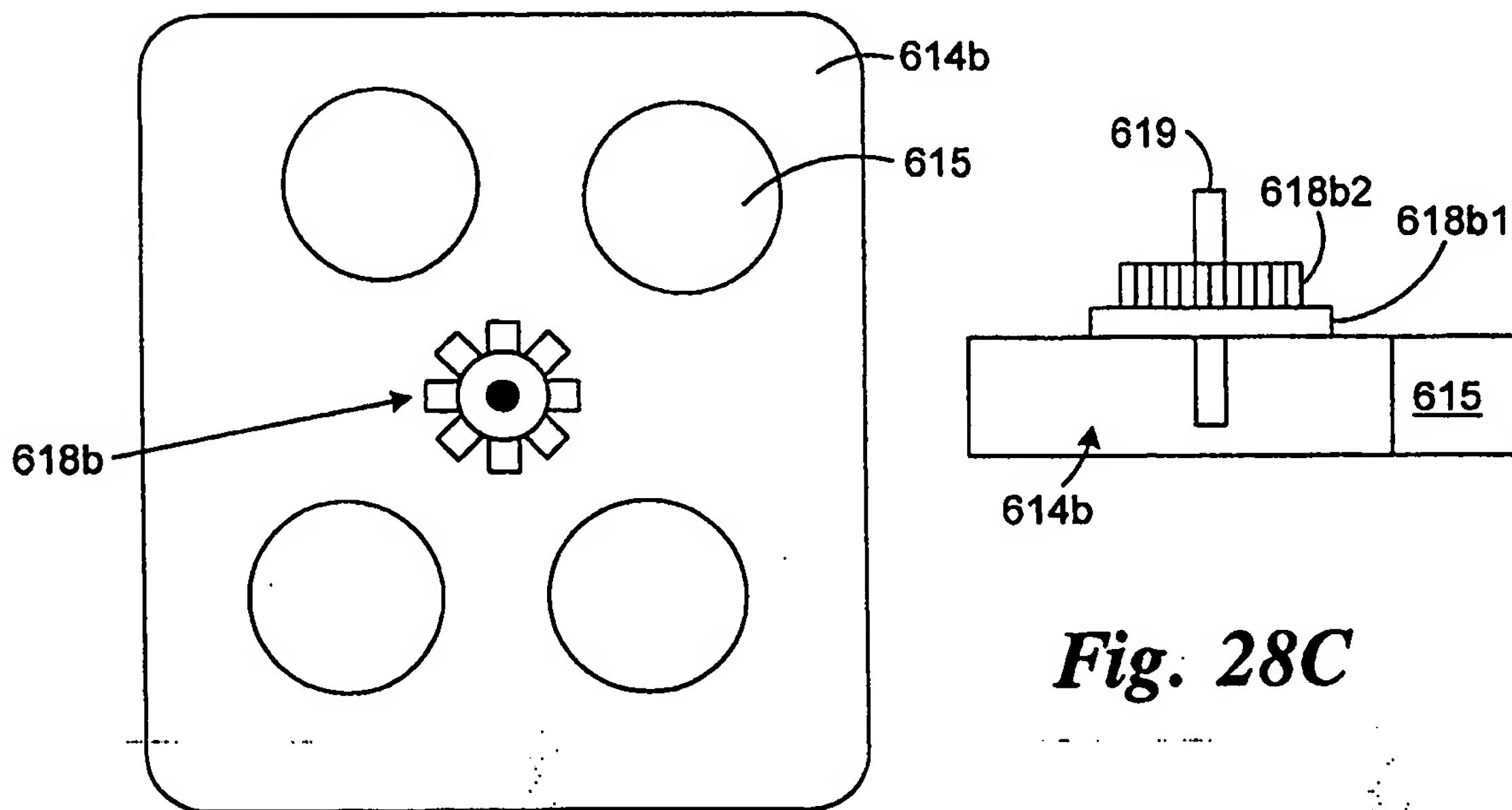


Fig. 28C

Fig. 28B

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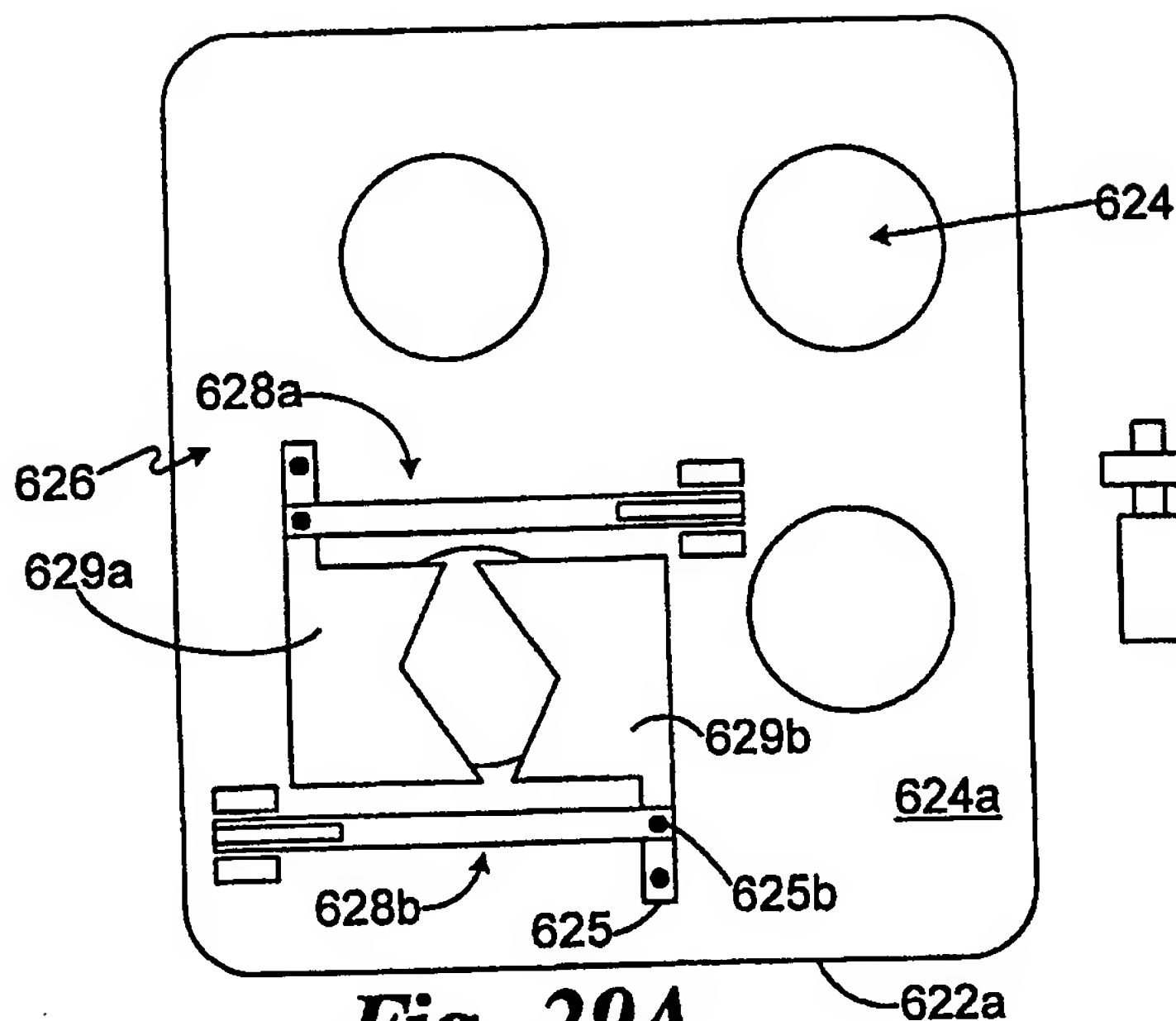


Fig. 29A

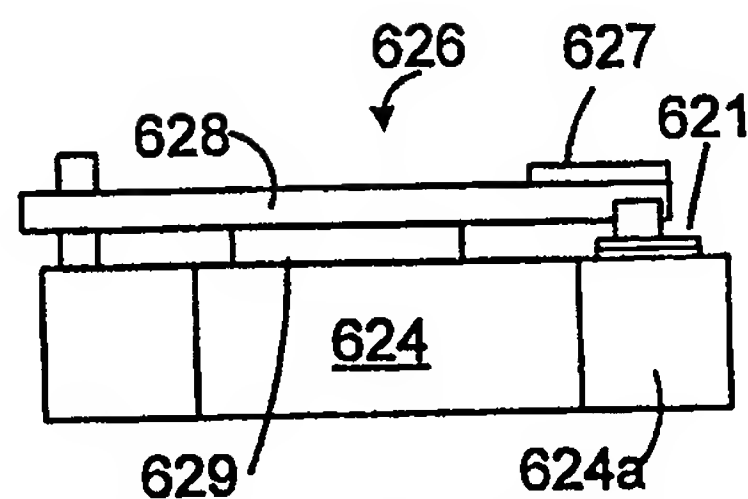


Fig. 29A-1

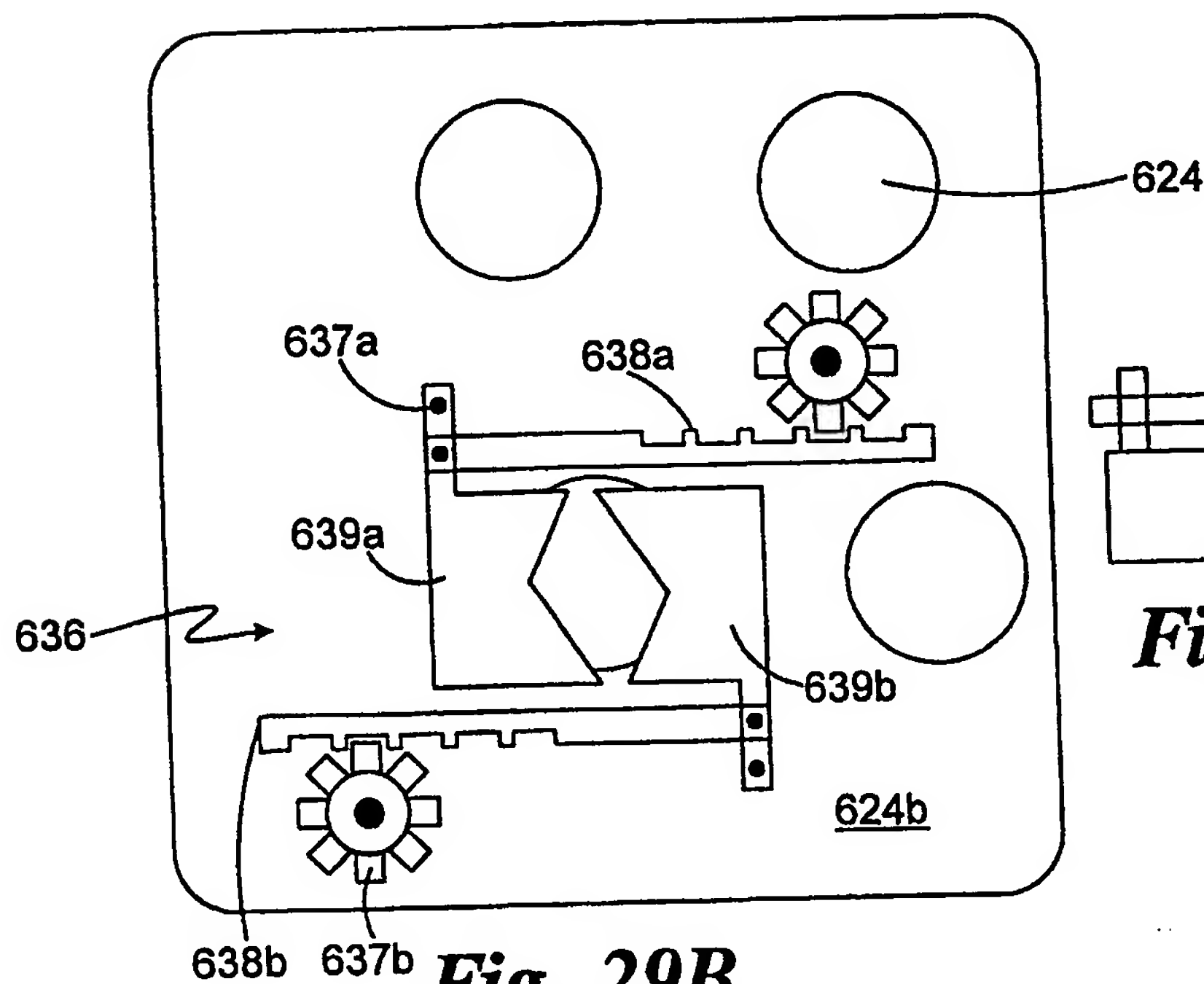


Fig. 29B

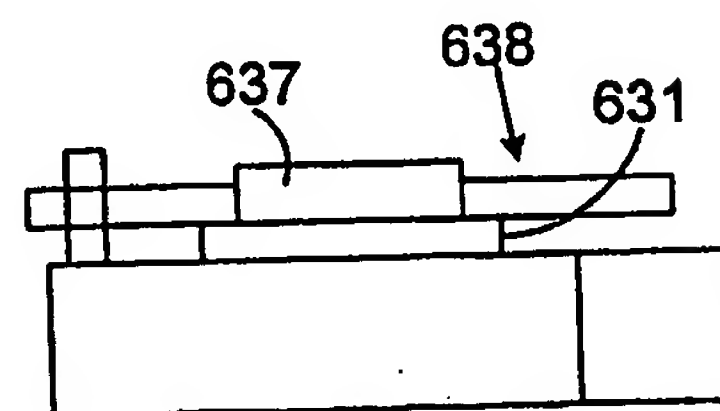


Fig. 29B-1

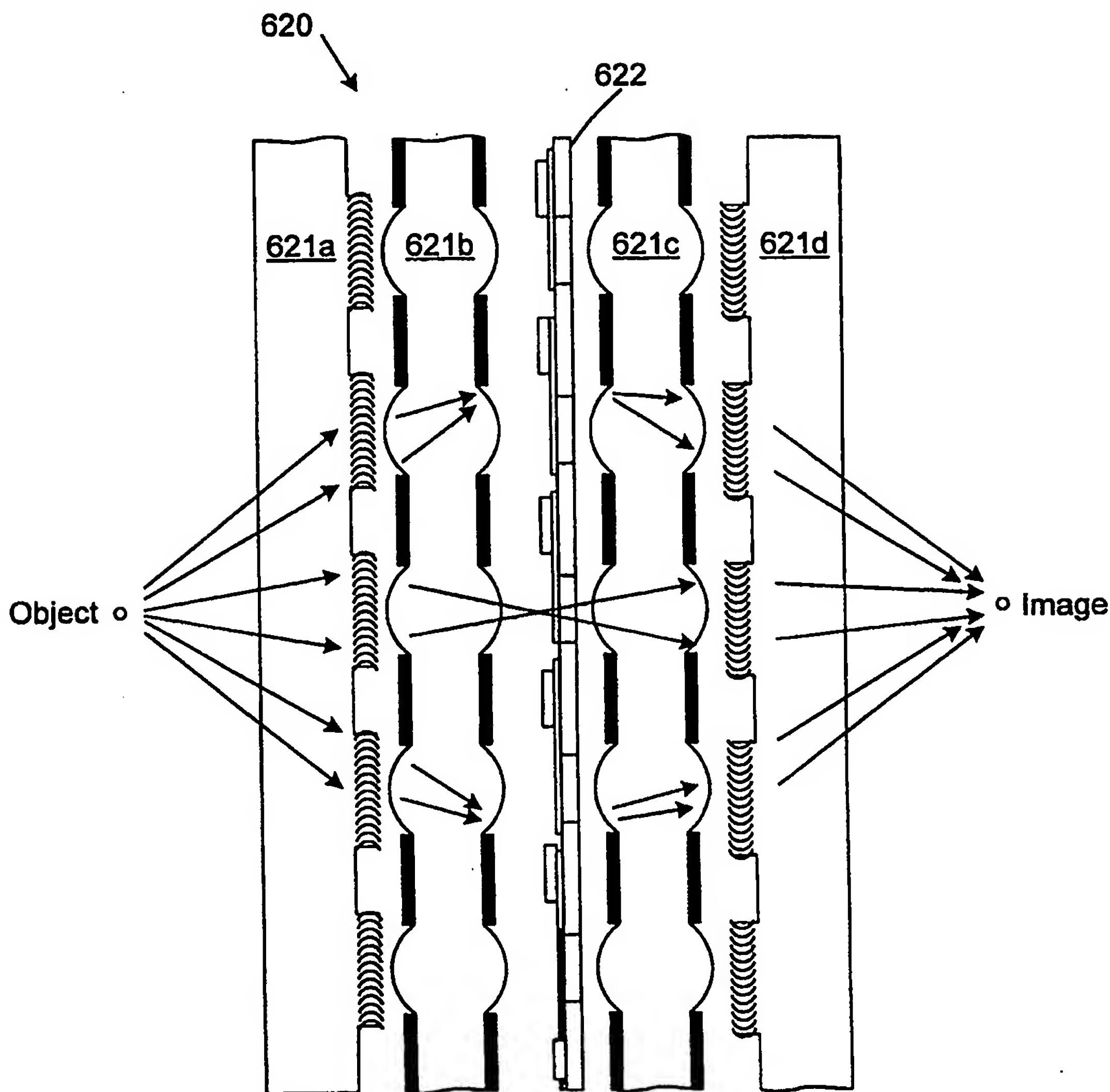


Fig. 29

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/01272

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : GO2B 27/10; GO2F 01/1335

US CL : 359/622, 621, 619; 349/95, 5

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/622, 621, 619

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS USPAT, APS JPOABS, APS EPOABS

search terms: (second or two)(2w)(lens?(2a)array# or (microlens?(2a)array#)) and magnif?

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4,632,522 A (ISHITANI) 30 December 1986 (30.12.86), figure 3, whole document.	1, 8, 13, 32, 57, 62-66 and 94
Y	US 5,463,498 A (GAL et al) 31 October 1995 (31.10.95) col. 13, lines 55-60, and figures 27 and 28.	79
A	US 4,512,641 A (MOCHIZUKI et al) 23 April 1985 (23.04.85), figures 3A and 3B.	
A	US 3,522,424 A (FRITSCH) 04 August 1970 (04.08.70), figure 1.	
A	US 3,357,770 A (CLAY) 12 December 1967 (12.12.67), figure 12.	



Further documents are listed in the continuation of Box C.



See patent family annex.

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O document referring to an oral disclosure, use, exhibition or other means	
P document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

06 MARCH 1998

Date of mailing of the international search report

08 JUL 1998

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